

WINDPOWER '97
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Annual Conference and Exhibition of the
American Wind Energy Association

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WELCOME ADDRESS--WINDPOWER 1997

**Randall Swisher, Executive Director
American Wind Energy Association**

Welcome to WINDPOWER '97 and Welcome to Texas, a state with a great future in wind energy. I'd first like to thank our cosponsors--DOE, NREL and Green Mountain Power--for their help in making this conference possible. I'd like to acknowledge the very significant role played by our Program Chairman, Dr. Andy Swift, and Emil Moroz, in doing so much work related to development of the program for this conference. I'd also like to thank our local host committee--especially Michael Osborne, Judy Carroll and Russel Smith--for everything they've done to make us feel welcome here, and in particular to TREIA, one of our local partners, for making the Whirlwind Tour of Texas Wind Facilities possible. Thanks also to Tom Foreman and the Lower Colorado River Authority for sponsoring last night's opening reception. Linda Redmond, our conference coordinator, did her usual superb job of managing the entire event, and has been delightful for all of us to work with. I hope you enjoy yourselves here and especially urge you to take advantage of our Tuesday Night Out activities which the local host committee arranged.

What is the state of wind power in 1997? On the positive side, wind energy continues its status as the fastest growing energy technology in the world, expanding at a 26% rate in 1996, the sixth year in a row in which we have experienced growth of more than 20%. The wind industry continues to build a stronger base internationally, as more and more countries take steps toward developing commercial scale wind energy projects.

We expect wind energy's strong worldwide growth to continue. Over the next ten years, we are projecting at least 30,000 MW of new wind capacity to be developed. That is roughly \$30 billion in economic value, to say nothing of the value of power sales. 30,000 MW is a conservative estimate; if there is any kind of significant response to the threat of global climate change, wind energy's growth could easily be twice what we are currently projecting.

Looking further out, the World Energy Council now projects world wind capacity of between 180,000 and 474,000 MW by the year 2020. That is only 23 years from now, but the mere thought of an industry that could approach half a trillion dollars in capital investment is enough to make my head spin. It is impossible to make reliable projections that far out, given all the uncertainties involved, but one thing is clear: wind energy technology will play an increasingly important role in providing electric power to meet the world's needs and we will continue to see strong growth throughout the world.

On the negative side, here in the U.S., with the spectre of electric industry restructuring and all its uncertainty greatly diminishing new power plant orders of any kind, new US wind capacity fell to only 10 MW in 1996. 1997 won't be too much more than that, but there is certainly a very different feeling within our industry as the future shape of the

electric industry becomes more clear. There is a sense that we have turned a corner, bottomed out, and significant things are happening both on the policy front and in the market.

On the policy front, we have three major agenda items we are pursuing that have particular importance to the market: 1) an extension of the wind PTC, which expires in mid-1999; 2) federal restructuring legislation; and 3) state restructuring legislation, with particular attention to California.

The wind PTC expires in mid-1999. We have made a strong case for an extension, and H.R. 1401 has been introduced by Rep. Bill Thomas, the third ranking member of the House Ways & Means Committee. On the Senate side, our leaders are Sen. Charles Grassley of Iowa and Sen. Jim Jeffords of Vermont, both members of the Senate Finance Committee. Key decisions on the future of the PTC will be made in the next month. While I believe we have made a good case, the tax committees epitomize Washington closed-door, power politics and it is always excruciatingly difficult for a small industry like ours to prevail. Right now the tax committees are saying that the only extensions that will be provided this year are for one year only and for credits expiring this year. That is not encouraging. We shall see, but this is the kind of fight where a stronger WindPAC could make a real difference.

Electric industry restructuring represents the biggest change in the industry in over 50 years--a fundamental shift away from vertically integrated monopolies to a competitive market for power generation, in which customers will have the opportunity to choose their power supplier.

There are pros and cons in this for wind energy. Competitive markets in which price is king present a real challenge to a relatively new technology with higher short term costs. We are trying to ensure that wind energy doesn't get hurt in the transition to competitive markets by advocating a Renewables Portfolio Standard--a relatively simple mechanism which would require all generators to meet a minimum standard of renewables production, or to meet their obligation through tradable credits. The RPS is competitively neutral, simple to administer and is consistent with competitive markets, depending upon market mechanisms to the maximum extent. But it would be a powerful tool in support of a renewable energy future, transforming the market for our technology by engaging all elements of the electric industry in an effort to acquire the lowest cost renewables.

We have been encouraged over the last year or two, as the RPS has gone from being a mere concept in Nancy Rader's mind to being *the* policy option that has been embraced by renewable energy advocates as the most effective means of encouraging commercially ready, bulk power renewables in a competitive market. Today, almost every major restructuring bill in the Congress has included some version of the RPS--Congressmen Schaefer and Markey in the House as well as bills introduced by Sen. Bumpers and Sen. Jeffords. We have a long way to go, however; the RPS is a target that competing technologies such as coal and gas have started to go after, and we will have to fight every

step of the way. In addition, I don't expect federal legislation anytime soon; there is no consensus that will allow a federal restructuring bill to move forward this year, or possibly even next. In the meantime, however, pressure from advocates for customer choice continues to build, and states around the country are moving at varying speeds toward allowing power suppliers direct access to the customer. It is happening first in parts of the Northeast, and in California, the home of most of the U.S. wind capacity, where customer choice will arrive next January 1, but, in varying degrees, the trend is nation-wide.

The California restructuring battle has been an intense effort lead by Nancy Rader over the course of more than a year. We forged an effective coalition with the geothermal, biomass and solar thermal industries in support of a state RPS. The state PUC embraced the RPS as their recommended policy for dealing with renewables in restructuring, but when we got to the state legislature, disarray within the environmental/sustainable energy community left us with a weaker and less effective result. Although half a billion dollars sounds like a lot, in a state like California it doesn't go far among many competing interests. Nevertheless, largely due to Nancy's capable analysis and the staunch support of our membership in California, wind did better than any other technology in the battle, and should see significant new project opportunities as well as support for existing projects (which should facilitate repowering where appropriate). The battle isn't over; we need your continuing support and involvement, but we are hopeful that the outcome will be favorable for wind. We expect final action by the California legislature by August.

I believe customer choice is inevitable throughout the U.S. and that no state will be in a position to hold out indefinitely. If differences in state policies become a burden to interstate commerce in electricity, the Congress will act, and we will have federal legislation that sets certain market rules for competition. I don't want to imply this will happen quickly, but it will happen. It is essential that those market rules provide for fair competition, including adequate consideration of the environment.

But customer choice is good for wind energy--at least it should be if we do it right--and it is a big part of the reason business prospects for wind energy look better in the U.S. We know that significant numbers of consumers want clean energy, and if given the chance, will take advantage of the opportunity. Smart Utilities know that if they aren't prepared to offer Clean Energy to their environmentally-minded customers, some other power supplier will. Thus, we see growing numbers of utilities getting interested in wind energy as the most cost-effective way to generate substantial renewable kWhs. And we see growing numbers of power marketers, ranging from Fortune 100 companies such as Enron to small renewable energy start-ups, getting engaged in wind energy.

Thus, we project substantial growth in U.S. wind capacity over the next decade. Currently, we project 600 MW before the end of the decade. We believe this is conservative and really doesn't account for much of the Green Market's impact. We are currently projecting somewhat more than 3000 MW over the next decade; again, a conservative estimate that we believe could well be eclipsed by events.

But the future is rarely what we expect it to be. Five years ago, who would have predicted the imminence of customer choice? Five years from now, what unanticipated change in circumstances will we face? Although electric industry restructuring is the major strategic driver for our technology today in the U.S., how will the passage of time affect the other major strategic force, global climate change? Will that issue finally begin to be reflected in worldwide policy changes? How can the international wind energy community work collaboratively to make that a reality? Despite the millions of dollars that have been spent on propaganda designed to confuse the debate--and that campaign has been effective at raising considerable skepticism within the Congress--the Big Lie technique can only work for so long. There is a strong scientific consensus and a growing public awareness that concerted action to address global climate change is the prudent and responsible thing to do. Over the next five years, this issue will begin to drive policy in ways that have more and more impact on the worldwide market for wind energy technology.

As excited as we are by the Green Market and all its potential, we are also sobered by the growing recognition of how fragile that market could be, of how dependent it is upon maintaining the confidence of consumers that what they are purchasing is really making a difference for the environment. Protecting the credibility of the wind industry and renewable energy marketers with consumers ought to be very high on our list of priorities. We need to ensure that consumers who want to purchase renewables do indeed end up buying green power, that they don't end up later believing they were misled into something much less environmentally pure than they intended. That is part of the reason for the growing amount of attention being paid to disclosure and certification related to renewable energy markets. That debate isn't close to being completed, but it will be important in safeguarding the credibility of the Green market.

All this debate about the Green Market brings us face to face with some important things to remember about our technology. Wind energy is fundamentally different than coal or gas or nuclear, and I'm not just referring to our intermittence. We have strong public support because we are perceived to be an environmental technology; for our industry, that carries with it certain expectations.

Randy Udall recently circulated a thought provoking document that included one statement that particularly got my attention. He said, "Clean power is not just a product, but a value."

That relatively simple statement says a lot to me about our business:

- it says we must pay attention to the market for our product, and ensure that consumers get what they think they are paying for;
- it says that we are not just selling kWh that are indistinguishable from conventional generators, it says we are delivering a premium product that provides the customer not just electric power but an opportunity for them to contribute to a Cleaner world; there

are very few ways for marketers to product differentiate with electricity--selling environmentally preferable power is perhaps the most effective way;

- it says that the public looks at us in a different way; our industry represents the white hats in an industry that, at least in the public perception, has been dominated by gray if not black hats;
- it says that public expectations of our industry are also different, and we need to always be working to ensure that our actions are consistent with those expectations. At its core, Wind energy is an environmental technology. That is perhaps our most important advantage in the market, and it is not something we ever want to lose.
- Finally, it says to me that we are damned lucky to have this opportunity. It isn't everyone who has the chance to make a difference while making a living, but that is an important part of what we in the wind energy community share.

But I don't want to go overboard. It is important that we all share a common vision of wind energy's future. It is something else to make that vision a reality. If anything, we've been blessed with more than our share of visionaries; what we have lacked, if anything, is enough people with the skills required to really change the world. If we are to even think about transforming this into a half trillion dollar industry, what will be required is the difficult, challenging work of:

- advancing technology;
- bringing about fundamental changes in public policy;
- building and operating successful projects;
- building successful companies.

Let's keep that vision in front of us, all the while paying attention to the fundamentals of what is required for each of us to ensure that wind energy achieves its potential.

Thanks for being with us, and thanks for playing your part in bringing about our common future.

NAVIGATING THE NEW DEREGULATED LANDSCAPE:
OPPORTUNITIES AND RISKS FOR WIND ENERGY

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ABSTRACT

Major changes in the law governing the electric industry are underway, fundamentally altering how the generation and sale of electric power is regulated and how electric power is marketed in the United States. Legislative and regulatory initiatives promoting competition will create a variety of opportunities, and commensurate risks, for power generators, marketers, brokers, sellers, and purchasers.

To succeed in the new marketplace, suppliers of renewable energy must understand the changes occurring on the state and federal levels, and position themselves to take advantage of the opportunities available. In this environment, monitoring and participating in state and federal legislative and regulatory efforts will be crucial for maximizing opportunities for wind energy.

I. AN OVERVIEW OF THE CURRENT REGULATORY SITUATION

A. THE ELECTRIC INDUSTRY IS SUBJECT TO COMPREHENSIVE
STATE AND FEDERAL REGULATION

The electric industry is comprehensively regulated at both the federal and state levels. The federal government regulates the sale of electric power at wholesale and the transmission of electric power in interstate commerce. The states regulate primarily the generation, local distribution, and retail sale of electric power.

A complex scheme of statutes underlies the federal regulation of the electric industry. This scheme includes the Federal Power Act ("FPA"), which grants the Federal Energy Regulatory Commission (the "FERC") comprehensive authority over interstate transmission and wholesale sales of electric power; the Public Utility Holding Company Act of 1935 ("PUHCA"), which grants to the Securities and Exchange Commission regulatory authority over certain public utility holding companies, and the Public Utility Regulatory Policies Act of 1978 ("PURPA") which sets out the regulatory structure applicable to "qualifying facilities" ("QFs") operating cogeneration and small power production facilities. State utility regulation is governed by state regulatory statutes generally analogous to the FPA.

B. "DEREGULATION" IS THE CURRENT REGULATORY THEME IN THE ELECTRIC INDUSTRY

In the 1980s and early 1990s, "deregulation" became the guiding regulatory theme in numerous industries, including the airline, trucking, telecommunications, and natural gas industries. The deregulatory focus has now shifted to the electric industry. Many state and federal legislators have already concluded that restructuring the electric power industry and introducing more competition into the industry is essential to maximizing the industry's efficiency, allowing consumers to obtain better prices for electric power, and increasing the range of products and services offered.

1. FERC ORDER 888

Thus far, the FERC has led the effort to restructure the electric industry. On April 24, 1996, the FERC issued Order 888, its comprehensive blueprint for restructuring those portions of the electric industry subject to its jurisdiction. Order 888 instituted three fundamental changes. First, it ordered all jurisdictional electric utilities to provide "open access" to their transmission systems. Under open access transmission, providers must allow eligible customers to "wheel," or transmit, power across their systems. Second, Order 888 required electric utilities to "unbundle" their contracts and services. Sales of power on a delivered basis, i.e., sales that include both power and transmission, were required to be disaggregated, with each component sold - and priced - separately. Third, Order 888 set out the rules under which electric utilities would be able to recover their "stranded costs." Stranded costs are the costs of those prudently-incurred electric utility investments that are rendered uneconomic by electric industry restructuring.

Implementation of Order 888 has been ongoing for over a year, but it still has a long way to go. The FERC has still not acted on the initial round of electric utility rate filings associated with open access tariffs filed in July 1996, in compliance with Order 888. Likewise, the restructuring filings made by power pools pursuant to Order 888 are still winding their way through the regulatory process. The final structure of open access transmission and the rates applicable to such services are, accordingly, still uncertain.

2. FEDERAL LEGISLATIVE DEVELOPMENTS

While the FERC has taken significant steps to enhance the role of competition in the portions of the electric industry subject to its jurisdiction, both the United States Congress and state legislatures and regulatory commissions have taken steps to promote competition in

local electric distribution markets. As of June 1, 1997, four comprehensive electric restructuring bills had been introduced into the 105th Congress, along with several other bills dealing with more narrow electric restructuring issues. The bill introduced by House Majority Whip Tom DeLay (R-TX), H.R. 1230, is currently the most aggressive of the various restructuring measures, and calls for the implementation of full retail access by all states by January 1, 1999. The bill introduced by Sen. Craig Thomas (R-WY), S. 722, in contrast, sets no deadline for full retail competition.

Several of the bills addressing electric restructuring propose to eliminate what the utility industry portrays as obstacles in the road to competition. For example, legislation introduced in April by Sen. Alfonse D'Amato (R-NY) would repeal PUHCA. Additionally, each of the four comprehensive bills would repeal PUHCA and prospectively repeal PURPA. The conventional wisdom is that Congress will require the utility industry to eat its spinach before it can have dessert; repeal of PUHCA and PURPA will therefore not move forward unless retail competition legislation moves forward simultaneously.

Several of the restructuring bills pending before Congress have specific features encouraging or requiring production of renewable energy. These provisions range from the required renewable energy production quotas in some bills, to the deference to state programs proposed in others. The proposed federal legislation thus has significant potential impact on the wind power industry, both through implementation of electric industry restructuring in general and also through implementation of wind power-specific measures.

3. STATE LEGISLATIVE AND REGULATORY DEVELOPMENTS

Numerous states are moving toward retail competition, either through legislation or through action before the state utility regulatory commissions. Seven states, California, Oklahoma, Rhode Island, Pennsylvania, Maine, Montana and New Hampshire, have already adopted retail competition legislation. The most aggressive of those states, Rhode Island and California, are scheduled to implement full retail choice on January 1, 1998. Other states have instituted retail access pilot programs as a first step toward retail competition. A significant percentage of retail consumers nationwide will therefore have their choice of electric power provider in the near future.

It is in this environment of extremely rapid change on a variety of regulatory and legislative fronts that wind power producers must plan their commercial strategy.

II. DEFINING "THE LANDSCAPE" FOR WIND ENERGY PRODUCERS

In the past, the perspective most wind energy producers had on the market and the regulatory process was fairly simple. In most cases, the producer would build a project designed to satisfy the PURPA definition of a "qualifying facility." Once complete, that project would sell power to the local utility under a long-term contract. PURPA provided the producer with exemptions from the FPA, PUHCA, and most of the day-to-day regulatory issues relevant to non-PURPA power generators.

In the future, wind energy producers probably will fall into one of two camps. They may continue to qualify under PURPA and thereby enjoy the same regulatory status they have enjoyed in the past. Or they may find themselves participating in the electric power marketplace as something other than a QF. For this segment of the wind power industry, life is going to be very different and very interesting. But why would any wind power producer or facility become something other than a QF?

A. THE FUTURE OF PURPA QF STATUS

Wind power producers might find themselves operating as something other than QFs under a number of scenarios. First, congressional repeal of PURPA might eliminate QF status and all its benefits, at least for new wind power projects. As to existing projects, there does not appear to be any support on Capitol Hill for retroactive PURPA repeal.

However, what Congress intends to do and what it actually does sometimes are not the same thing. Some PURPA contracts link the utility's purchase obligation to the continued applicability of PURPA. Those contracts may be affected by a PURPA repeal, regardless of what Congress intends. At a minimum, it is unclear whether such contracts can be grandfathered. All wind power producers with existing QF contracts should carefully review those contracts to determine if the specific PURPA repeal language under consideration would pose problems for them.

Second, although current proposed federal legislation is designed to repeal PURPA on a prospective basis only, the legislative debate has not yet concluded. Notably, the debate over "stranded costs," one of the most difficult electric restructuring issues, has not been resolved. Estimates of aggregate stranded cost liability in the electric utility industry vary greatly but range as high as \$200 billion. One significant source of utility stranded costs is above-market purchase obligations from QFs. Given the magnitude of the stranded cost problem and its importance to the utility restructuring debate, wind power producers with existing QF contracts should not

simply assume that retroactive PURPA repeal is "off the table." They should monitor the stranded cost issue with an eye toward aggressive participation if existing QF contracts become a bargaining chip in the stranded cost debate.

Third, parties to existing QF contracts may want to consider renegotiating those contracts voluntarily in order to obtain the right to participate in increasingly competitive wholesale and retail power markets or in state-mandated "green power" programs. In some circumstances, maintaining QF status and continuing to sell power at avoided cost prices may be less desirable than terminating QF status and marketing "green power" at competitive rates or under state incentive programs.

Of course, if PURPA is repealed, no future projects will be QFs even if that status is maintained for all existing QF contracts and facilities. Therefore, those who are planning to build or operate new wind power projects must consider the possibility (some would say probability) that the facility will not be a QF or have the benefits of QF status.

Thus, there are several credible scenarios under which wind power producers would, voluntarily or involuntarily, enter the new competitive arena. For those producers, the regulatory landscape will be much more complicated than their historical QF status.

B. REGULATORY OPTIONS FOR NON-QF WIND POWER PROJECTS

Analysis of the regulatory options available to non-QF wind power producers must start with a question on which QF developers and operators rarely faced: "What is our commercial strategy?" That question is important because different regulatory structures are available depending upon whether a wind power producer intends to sell power exclusively into wholesale markets.

If only wholesale sales are contemplated, a wind power project may qualify for "exempt wholesale generator" ("EWG") status. The primary benefit of EWG status is that EWGs are not considered to be electric utilities under PUHCA and are therefore exempt from nearly all of PUHCA's various and complicated restrictions.

If the wind power producer intends to make some sales at retail, or cannot qualify as an EWG for some other reason, it would not be eligible for any exemptions from PUHCA or the FPA. Such a producer would be treated as an "independent power producer" ("IPP") and would be treated for regulatory purposes like any independent producer of electric power.

C. FERC RATE REGULATION OF EWGs AND IPPs

Both EWGs and IPPs are subject to the same regulatory treatment at FERC, even though EWGs are exempt from PUHCA. FERC has jurisdiction over all sales at wholesale in interstate commerce by EWGs or IPPs. Accordingly, both types of entities are required to file their power sales contracts with the FERC for acceptance pursuant to the FPA. FERC will accept contracts for filing if the rates are shown to be "just and reasonable" in one of two ways. The conventional approach is to demonstrate that the proposed rates are cost-justified. Alternatively, both EWGs and IPPs may, under certain circumstances, qualify for market-based rates.

To obtain market-based pricing of individual contracts, the EWG or IPP would file with the FERC a request for market-based pricing of a particular contract. The seller would then demonstrate that it either lacks or has adequately mitigated any market power and does not control barriers to entry into the relevant market.

EWGs or IPPs can also seek market-based pricing authority on a "blanket" or generalized basis. To obtain such authority, the applicant would have to show that it lacked or had adequately mitigated market power in the power sales markets in which it wished to compete and otherwise did not control barriers to entry. If the factual showing was adequate, the Commission would grant the applicant blanket power sales authority generically authorizing the applicant to sell power at negotiated market-based rates subject only to certain after-the-fact filing and reporting requirements.

A complete analysis of the Commission's market-based rate policies is beyond the scope of this presentation. However, wind power producers that wish for their projects to operate as EWGs or IPPs should be aware that market-based pricing either on a contract or blanket basis is generally available depending on the facts and circumstances for each individual applicant. Wind power developers seeking to rely on market-based rates should carefully examine the Commission's policies and precedents to assure they can satisfy the Commission's standards.

III. OPPORTUNITIES AND RISKS IN THE COMPETITIVE MARKETPLACE

Participating in the new competitive marketplace offers wind power producers both opportunities and risks that they may not have faced before. These opportunities and risks vary significantly depending on the specific commercial objectives of the project at issue. The following analysis gives examples of the complete spectrum of these risks and opportunities. Individual wind power producers may avoid certain of the risks and focus on certain opportunities, depending on their business strategy.

A. OPPORTUNITIES IN THE NEW ENVIRONMENT

The most significant (and obvious) opportunity associated with the new competitive electric industry is the opportunity to sell power into an open, competitive market or under state green power incentive programs. Open access to transmission and distribution systems will give wind power producers access to power markets across the country, both at wholesale and retail.

Responding to this new freedom requires a disciplined analysis of what commercial strategy to pursue. Wind power producers can focus on wholesale markets or retail markets, or some combination of the two. Similarly, they can sell power at their interconnect with their neighboring utility, or can become "downstream" sellers and contract for transmission capacity in order to sell power in distant markets.

1. COMPETING IN WHOLESALE POWER MARKETS

For producers that choose to sell in wholesale markets, several regulatory and commercial issues must be considered. If downstream power markets offer better opportunities than selling at the nearest interconnect, the wind power producer will need to obtain transmission service, and will, as a result, need to become conversant with the OASIS ("Open Access Same-Time Information System") in order to locate available transmission capacity and contract for its use. The producer will need to become familiar with the different types of transmission service available (*i.e.*, firm and non-firm transmission and the various ancillary services) and how these services are priced. It also may find that transmission availability or pricing rules create impediments to implementing the producer's commercial strategy. In such situations, it could change its focus to a different market where such impediments can be avoided, or affirmatively use the regulatory process to seek changes in the applicable transmission tariffs.

Analyzing the purely commercial and financial issues that will arise for a wind power producer competing in wholesale markets is beyond the scope of this paper, but even issues that appear to be purely commercial may give rise to new regulatory issues for wind power producers. For example, successful power sellers will inevitably develop sophisticated risk management programs specifically tailored to their power sales strategy. With the advent of the electricity futures market, power sellers now have access to appropriate exchange-based tools to use in devising hedging strategies. Additionally, over-the-counter products such as collars, swaps, and other instruments will become increasingly available in the electric power industry, as they have in the natural gas industry. Participating in futures markets or developing risk management strategies will give rise to new legal questions and regulatory issues.

2. COMPETING IN RETAIL POWER MARKETS

In addition to the issues discussed above in the context of a wholesale power sales strategy, a wind power producer seeking to participate in retail markets must consider certain additional issues. Open access under Order 888 applies only to FERC-regulated transmission facilities. Access to state-regulated distribution lines is subject to state regulatory initiatives. Currently, state retail access is a patchwork. As more and more states implement retail access, the available retail market will expand accordingly. Wind power producers seeking to participate in retail markets must keep abreast of the rapidly growing scope of retail access in order to target sales efforts on the best available markets.

The terms and conditions of state-mandated open access to retail distribution lines may differ significantly from FERC-ordered open access to transmission lines. Power sellers seeking to participate in retail markets must become conversant in the terms and conditions and pricing of open access on distribution facilities.

The commercial and financial issues associated with a retail sales strategy are also complex. For example, a wind power producer seeking to participate in retail markets does not need to do so directly by selling to individual residential and commercial customers. It could sell solely to "load aggregators" who will in turn seek out individual residential and commercial customers to form collective purchasing entities. As retail power markets evolve, a broad spectrum of prospective customers will likely develop.

One very important potential opportunity for wind power developers is participating in state-mandated renewables set-aside programs. The FERC recently ruled that Iowa's renewables set-aside statute did not conflict with federal law. Accordingly, significant uncertainty regarding the legal viability of such programs has been removed. States that have not yet adopted such programs could be encouraged by FERC's decision regarding Iowa's program to institute their own set-asides for renewable power.

State renewables set-aside programs provide an attractive market for wind power producers but do not remove the various federal and state regulatory requirements discussed above. Specifically, consistent with FERC's decision involving Iowa's program, FERC retains jurisdiction over wholesale power sales contracts under such programs, and must approve the rate negotiated between the utility and the renewable energy provider. Obtaining FERC approval of such rates is one of the significant risks corresponding to the opportunity offered by state set-aside programs.

B. RISKS FOR WIND POWER PRODUCERS IN THE NEW COMPETITIVE ENVIRONMENT

Several risks to wind power producers -- including the risk that congressional repeal of PURPA might inadvertently undermine existing QF sales contracts -- have already been discussed. In addition to such risks inherent in the current legislative process, numerous other risks unique to the new competitive landscape have arisen. Most notable is the market risk associated with selling power in a competitive environment. The purely commercial risks associated with competition are beyond the scope of this paper. The regulatory and legal risks, however, are no less serious than the commercial risks.

First, sellers choosing to participate in downstream markets are dependent upon the availability and price of transmission service. If transmission service becomes unavailable or unreliable, a wind power producer may find itself unable to reach or compete in an important market. Likewise, a producer may be priced out of an important market if the transmission rates it must incur increase. Under either of these scenarios, the wind power producer may be forced to employ the regulatory process to remedy the competitive problem.

Second, all wind power producers that are subject to the Federal Power Act (*i.e.*, all EWGs and IPPs) face significant regulatory risk as to their new power sales contracts. Wind power producers must seek FERC approval of new power sales contracts, and must show that their proposed rates are just and reasonable on a cost or market basis. If the producer is unable to make the required showing, its negotiated contract rate may be reduced. A FERC proceeding could be finally decided long after service under a contract has begun, thus giving rise to the possibility of substantial refunds. The wind power producer negotiating power sales contracts must be careful to assure that its sales price is capable of being fully supported under either a cost or market-based approach.

Third, the requirement that power sellers file their contracts with the FERC for approval raises complications in terms of keeping certain sensitive commercial information confidential. FERC's regulations provide for confidential treatment of certain types of sensitive commercial information. However, the requirement that jurisdictional power sales contracts be filed with the Commission for approval is at odds with the principle of confidentiality. In an increasingly competitive world, confidentiality of the terms and conditions negotiated by wind power producers and the purchasing utilities may be increasingly sensitive, and accordingly, wind power producers should understand their alternatives before structuring and executing their contracts.

Fourth, new risks have arisen even for those wind power producers that currently qualify as QFs and intend to continue as QFs. In its zeal to spread "open access" to as much of the national power grid as possible, the FERC recently affirmed that it will require QFs that own transmission facilities to provide "open access" if any affiliate seeks authority to market power. For some wind power producers, this new policy may force an undesirable choice between setting up an affiliate to sell power in the competitive marketplace, and maintaining control over transmission facilities that were built exclusively to transport QF power.

IV. CONCLUSION

There is an ancient Confucian curse that translates to "may you live in interesting times." Participants in the wind power industry may be living that curse. They should not lose sight of the fact, however, that this is a time not just of new risks, but of unprecedented new opportunities. The developers and operators that are most nimble in locating those opportunities and structuring their business strategy to insulate themselves from the risks will reap the benefits of the new restructured electric power industry.

Analysis of Renewable Portfolio Standards

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A national RPS would increase the fraction of U.S. electricity generation from renewable technologies at least cost. It would help ensure that the cost and performance of these technologies would improve with manufacturing experience, scale economies, and learning-by-doing from their integration into electric systems. Thus, their economic, environmental, energy security, and sustainability benefits would be realized.

Renewable resources bring many benefits to society. They can reduce carbon dioxide emissions at the national level, and ozone precursors, particulates and toxic metals at the regional level, by displacing fossil-fuel generation. They can provide fuel diversity and price stability, as well as energy security and independence. They can provide economic benefits, especially in rural areas in need of economic development opportunities. Finally, U.S. leadership in renewable energy technology manufacturing and expertise can contribute importantly to our role in helping to meet the sustainability and development goals of *Agenda 21*.

However, the prospects for renewables, and thus their non-price societal benefits, could be threatened in a restructured electric generation industry, in which price competition will govern generation resource acquisition and use. Moreover, the potential cost and price benefits that could otherwise derive from scale economies and technological learning could be lost. A national *Renewable Portfolio Standard (RPS)* is an innovative policy that would ensure minimum levels of renewables in the electric resource mix, to help secure their environmental, economic, and fuel diversity benefits.

With trading of renewable credits, an RPS can harness competitive forces, with modest administrative requirements, to achieve the renewable generation minimum at least cost. There would be two markets for sellers of renewable kilowatt-hours: one for the *electricity* which would compete in power markets on the local grid, and one for the renewable energy *credits* which could be sold anywhere in the U.S. Those who generate more than the required percentage would sell their excess credits, and those who generate less would buy needed credits. Thus, each retail supplier would meet the minimum requirement by either generating renewable energy, purchasing renewable energy or purchasing renewable energy credits.

Tellus Institute has performed analyses using the DOE's NEMS model for three RPS requirement levels by the year 2010, 4%, 8% and 10% of generation as non-hydro renewables, i.e., wind, solar, biomass, municipal solid waste to energy, and geothermal.

The premium for renewable energy, and thus the credit trade price, ranges from 1 to 2.5 cents per kWh for the three targets, while the impact on electricity prices would range from 0.04 to 0.26 cents per kWh, or 20 cents to \$1.30 per month for a household with 500 kWh electricity demand. Substantial reductions of carbon dioxide emissions as well as some other pollutants would be realized.

Tellus Results

Non-hydro Renewables as a Percent of 2010 Generation

	4%	8%	10%
Credit trade price 1995 c/kWh	1.03	2.16	2.56
Electric Price Impact 1995 c/kWh	0.04	0.17	0.26
National Resource Cost (Net) \$1995 Billion ¹	1.15	5.55	8.70
Typical Household Impact 1995 \$/Month	0.20	0.85	1.30
Carbon-dioxide Reductions Million Tons	36.7	121.0	161.3
(% of 1990 Emissions)	(2.1)	(6.9)	(9.3)
% Wind	32	49	49
% Solar	4	16	22
% Geothermal	29	16	13
% Biomass	10	7	6
% MSW ²	25	12	11

The *percentage* of total renewable generation from each of the renewable technologies changes with the size of the RPS requirement, while the *absolute* amount increases substantially from their current levels and from the levels they would achieve in 2010 without the RPS.

For more information on renewable portfolio standards, please see the article by Bernow, Dougherty, and Duckworth entitled, "Can We Afford a Renewables Portfolio Standard?" in the May 1997 issue of the *Electricity Journal*.

¹ This is the difference between the capital fuel and O&M costs as reflected in prices through cost-of service capital recovery and reflects the high front-end recovery in the early years of service for units coming in near 2010. This, plus the fact that the 2010 cutoff does not reflect the long-term tradeoffs that are embodied in the credit trade price renders this national resource cost impact somewhat high. The low to high range would be \$0.28 to \$1.15 Billion (at 4%), \$2.05 to \$5.55 Billion (at 8%) and \$3.50 to \$8.7 Billion (at 10%).

² Generation from MSW is not changed with the RPS, reflecting a fixed amount from current generation plus planned additions; hence its declining share.

ELECTRIC INDUSTRY RESTRUCTURING, ANCILLARY SERVICES, AND THE POTENTIAL IMPACT ON WIND

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INTRODUCTION

The new competitive electric power environment raises increased challenges for wind power. The DOE and EPRI wind programs have dealt extensively with the traditional vertically integrated utility planning and operating environment in which the host utility owns the generation (or purchases the power) and provides dispatch and transmission services. Under this traditional environment, 1794 MW of wind power, principally in California, have been successfully integrated into the U.S. electric power system. Another 4200 MW are installed elsewhere in the world. As issues have arisen, such as intermittency and voltage regulation, they have been successfully addressed with accepted power system procedures and practices (Putnam 1996 and Utility Wind Interest Group 1992).

However, FERC Order 888, *Promoting Wholesale Competition Through Open Access Non-Discriminatory Transmission Services by Public Utilities*, issued in April of 1996 and modified in March 1997 requires electric utilities to provide open access, non-discriminatory transmission service. The Commission's stated goal is "to remove impediments to competition in the wholesale bulk power marketplace and to bring more efficient, lower cost power to the Nation's electricity consumers." FERC is doing this by requiring transmission utilities to unbundle, and charge separately for, all of the ancillary services required to make the electric system operate. This unbundling requires cost and administrative consideration of operating, dispatch, and transmission issues that had previously not been a concern in the use of wind power and that had not been considered explicitly in rates. For an intermittent, non-dispatchable resource such as wind, this raises questions about which ancillary services wind plants will be able to sell, which they will be required to purchase, and what the economic impacts will be on individual wind projects.

This paper begins to look at issues of concern to wind in a restructured electric industry. The paper first briefly looks at the range of unbundled services and comments on their unique significance to wind. To illustrate the concerns that arise with restructuring, the paper then takes a more detailed look at a single service: regulation. Finally, the paper takes a brief look at technologies and strategies that could improve the competitive position of wind. Further details can be found in the report "Ancillary Services and Their Impact on Renewable Resources - Wind as an Example" which will be available this summer.

Restructuring and ancillary services do not address new physical phenomena or new physical interactions between wind resources and the electric system. What they do address is the way provision and consumption of services is determined and how providers and consumers of those services will be compensated or charged. In a restructured electric power industry it is necessary to think in terms of providers and consumers of services rather than in terms of generators and loads. A generator may be a provider of some services and a consumer of others. Ultimately, a sustainable market will require that individuals be compensated for what they actually provide and charged for what they actually consume, with both determined through performance monitoring.

A major issue for wind in the restructured marketplace is the magnitude, frequency, and trends of short term

(1 to 10 minutes) power fluctuations. Data on this are lacking because 1) previous regulatory treatment recognized only energy and capacity payments, 2) fluctuations were not generally considered a problem in California, and 3) there have not been opportunities to examine the fluctuations in new projects. Thus, this paper is more illustrative than analytical and serves to alert the wind community of data requirements for analysis of ancillary services as well as the implications of ancillary services themselves. Examples, when given, are illustrative only. While the data used is real, it is not representative of wind plants in general, any specific equipment configuration, or even of the site it was collected from. DOE, EPRI, NREL, and partners are collecting short-term power data as part of the Turbine Verification Program and are planning to support collection of similar data from other projects as partners become available.

ANCILLARY SERVICES AND THEIR RELATIONSHIP TO WIND ENERGY

Ancillary services are those functions performed by the electrical generating, transmission, system-control, and distribution-system equipment and people that support the basic services of generating capacity, energy supply, and power delivery (Hirst and Kirby 1996a). The overall cost of ancillary services in the U.S. is 6 to 20% of total generation and transmission costs, equivalent to approximately \$12 billion a year or 0.4 ¢/kWh (Kirby and Hirst 1996). Key ancillary services are listed in Table 1 grouped according to the FERC's requirements for provision and acceptance. FERC requires transmission providers to provide, and transmission customers to accept the first two services: 1) scheduling, system control, and dispatch, and 2) reactive supply and voltage control. Transmission providers are required to offer four more services: regulation, spinning reserve, supplemental reserve, and energy imbalance, but transmission customers are free to obtain these services from other sources. Transmission providers are not required to offer the remaining services; transmission customers are free to obtain these remaining services from third parties or provide them themselves.

FERC did nothing in the definitions to address methods to quantify either the services or the prices. FERC will allow market-based pricing if the transmission provider can demonstrate that it does not possess market power and will require cost-based pricing otherwise. But, it is not clear how to unambiguously determine the cost-based price for a separate service, such as supplemental operating reserve, where a single piece of equipment helps provide several services. Determining the market-based price requires knowledge of both the supply and demand in the rest of the market, along with the current spot price for energy.

Table 2 examines these services from the perspective of wind power. The individual characteristics of each wind plant, the equipment employed, the wind resource itself, the electric grid it is connected to, and the electric markets it has access to, will determine the importance of each service to that wind plant. Generators will buy or sell ancillary services, depending on their capabilities and the burdens they place on the electrical system. Plant designers, owners, and operators will need to evaluate their own situation, but Table 2 gives a good starting point to consider interactions between wind plants and electric markets in general.

Wind plants will want to pay close attention to services related to balancing generation and load (regulation, operating reserves, load following, energy imbalance, and backup supply). Older line connected induction generator based plants could have problems with the voltage control service depending upon the specific wording of the service rules. Services such as system control, real loss replacement, and black start will likely not pose problems for wind plants that are different from the problems other generators face.¹ Two services, voltage control and network stability, may provide opportunities for new plants that are connected to the grid through solid-state converters to sell services to the grid if they are located where the service is required.

¹The relatively small size of many wind plants coupled with frequent schedule changes could result in high charges for system control, depending on how the control area prices this service.

Table 1. KEY ANCILLARY SERVICES AND THEIR DEFINITIONS

Service	Description
Services FERC requires transmission providers to offer and customers to take from the transmission provider	
Scheduling, system control, & dispatch	The control-area operator functions that schedule generation and transactions before the fact and that control some generation in real-time to maintain generation/load balance
Reactive supply and voltage control	The injection or absorption of reactive power from generators to maintain transmission-system voltages within required ranges
Services FERC requires transmission providers to offer but which customers can take from the transmission provider, third parties, or self-provide	
Regulation and frequency response	The use of generation equipped with governors and automatic-generation control (AGC) to maintain minute-to-minute generation/load balance within the control area to meet NERC control performance standards
Operating reserve - spinning	The provision of generating capacity (usually with governors and AGC) that is synchronized to the grid and is unloaded that can respond immediately to correct for generation/load imbalances caused by generation and transmission outages and that is fully available within 10 minutes
Operating reserve - supplemental	The provision of generating capacity and curtailable load used to correct for generation/load imbalances caused by generation and transmission outages and that is fully available within 10 minutes
Energy imbalance	The use of generation to correct for hourly mismatches between actual and scheduled transactions between suppliers and their customers
Services that FERC recognizes but does not require transmission providers to offer	
Load following	The use of generation to meet the hour-to-hour and daily variations in system load
Backup supply	Generating capacity that can be made fully available within one hour, used to back up operating reserves and for commercial purposes (as opposed to being required for reliability)
Real losses	The use of generating equipment to compensate for the transmission-system losses from generators to loads
Dynamic scheduling	Real-time metering, telemetering, and computer software and hardware to electronically transfer some or all of a generator's output or a customer's load from one control area to another
Black-start	The ability of a generating unit to go from a shutdown condition to an operating condition without assistance from the electrical grid
Network stability	Maintenance and use of special equipment (e.g., power system stabilizers and dynamic braking resistors) to maintain a secure transmission system

Dynamic scheduling is not an ancillary service in the sense the others are; it is not a service the grid requires to maintain reliability. Dynamic scheduling provides the ability to electronically transfer the full regulating, reliability, and commercial burden (or benefit) of a generator or load from one control area to another by telemetering MW production or consumption information to both control areas every 2-8 seconds. Wind plants may wish to use dynamic scheduling to access more favorable markets or to combine resources to obtain a more favorable performance profile, (Hirst and Kirby, 1997).

Table 2. ANCILLARY SERVICE CONCERNS FOR WIND

Service	Of special concern to wind?	Will wind buy or sell the service?	Mitigating Strategies and Technologies ^a	Time Frame
System control	No	Buy	Dynamic scheduling	
Voltage control	Possibly for older plants	Newer plants may sell service	Solid state power system interface	Seconds
Regulation	Yes	Buy	Inter- and intra-plant aggregation (diversity), array control, dynamic scheduling, re-optimization, financial/physical hybrid, short-term energy storage	1-2 min
Spinning reserve	Yes	Buy	Short-term (10-20 min) forecast, dynamic scheduling, aggregation, hybrid, re-optimization, array control	Seconds to 10 min
Supplemental reserve	Yes	Buy	Short-term forecast (20 min - 1 hr), dynamic scheduling, aggregation, hybrid, re-optimization, array control	<10 min
Energy imbalance	Maybe	Buy	Short-term forecast (1 hr), aggregation, hybrid, re-optimization, array control, dynamic scheduling	Hourly
Load following	Yes	Buy	Short-term forecast (1 - 3 hr), re-optimization, dynamic scheduling, hybrid, array control	Hours
Backup supply	Yes	Buy	Forecast, dynamic scheduling, hybrid, array control	>30 Min
Real losses	No	Buy		Hourly
Dynamic scheduling ^a	Yes	Buy	May help wind reach better energy and services markets	Seconds
Black-start	No	Buy		
Network stability	No	Newer plants might sell service	Solid state power system interface, machine design, analysis demonstrating benefit	Cycles

^aDynamic scheduling is both a service and a possible mitigating technology since it can be used to move generation from one control area to another or to aggregate non-contiguous resources.

SERVICE QUANTIFICATION AND PRICING

Though the ancillary services are now fairly well defined and FERC has established which services must be offered by transmission providers, methods for measuring and pricing services have not been determined. Most tariffs filed to date simply allocate the overall system requirement for each service to all customers based upon energy consumption. That is, they set a \$/kWh price for each service based upon basic energy consumption. This is simple and straightforward. It is also wrong, and in our opinion will not last.

As deregulation progresses, competitive pressures will likely force an allocation based upon actual service consumption and compensation based upon actual service provision. Taking the regulation service as an example, Figure 1 shows the variation in load for an aluminum smelter and a steel mill over an hour. The aluminum smelter will eventually realize that it is imposing a much smaller regulation burden on the system than the steel mill and it will negotiate a reduced rate for regulation. If the host control area will not offer a reduced rate the aluminum smelter will seek service from someone that will. Though this example, chosen for its clarity, is of two loads the principle holds equally for non-regulating generation.

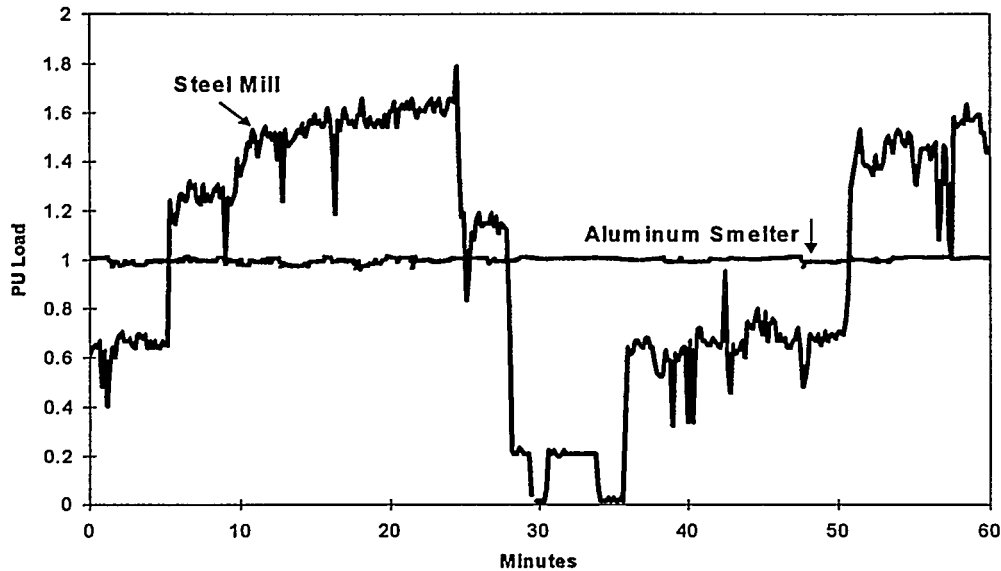


Figure 1 VARIATION IN STEEL MILL AND ALUMINUM SMELTER LOADS FOR 1 HOUR MEASURED AT 10-SECOND INTERVALS

Some proposals call for compensating generators that provide regulation service simply based upon the capacity they dedicate to regulation. But, generators exhibit differences in performance when supplying regulation service. Examining two similar fossil-fired steam plants in a Midwestern control area, Hirst and Kirby (1996b) found that while one followed automatic generator control (AGC) signals well the other actually contributed 31 MW to the area control error over the hour studied. There are more pronounced differences between types of generating units with hydro units generally performing better than thermal units. Owners of better performing generators will want to receive more compensation for the service they provide than that given to poorer performing units. In addition to the two options generally available to loads for obtaining more equitable treatment (lobbying the rule-making organizations and using dynamic scheduling to reach other markets) generators are able to choose which services they sell. When a generator chooses to sell into the regulation market it removes a portion of its generating capacity from the basic energy market and from the reserve markets. To the extent that one of these markets does not provide appropriate compensation the generation will be moved to the other markets.

For these reasons, we think that charging customers for ancillary services based upon their energy consumption and compensating generators based simply upon the capacity they dedicate to the ancillary service is not sustainable. FERC has already provided sufficient flexibility that market forces will drive compensation to reflect performance. Prices paid for each ancillary service will likely vary dramatically in time and location.

REGULATION AND FREQUENCY RESPONSE

Due to the variability of the wind resource, regulation and frequency response will be an ancillary service of special concern. A more detailed examination of regulation also serves as an example of the types of interactions between wind plants and the power system that will be important when examining other ancillary services. But first we must define what is meant by regulation. Figure 2 decomposes a hypothetical transaction into its components: base, ramp, and fluctuations. The base portion can be accommodated through block transactions while the ramp can be accommodated through manual scheduling and control. Fluctuations, however, require AGC and faster response from the generators that are to provide the required aggregate generation/load balance. Regulation and frequency response is the ancillary service that responds to these fluctuations. Analysis of system fluctuations and the generation response showed that the important characteristic is the standard deviation measured at the 1- to 2-minute level (Hirst and Kirby 1996b).

Three characteristics are of interest when evaluating regulation; the magnitude and speed of fluctuations and their correlation with other fluctuations. The lack of short-term correlation among individual loads or non-regulating generators means that aggregation greatly reduces the regulation requirement for the overall system. The regulation requirement for N transactions with equal but uncorrelated fluctuations is only $\sqrt{N}$ times the regulation requirement of a single transaction.

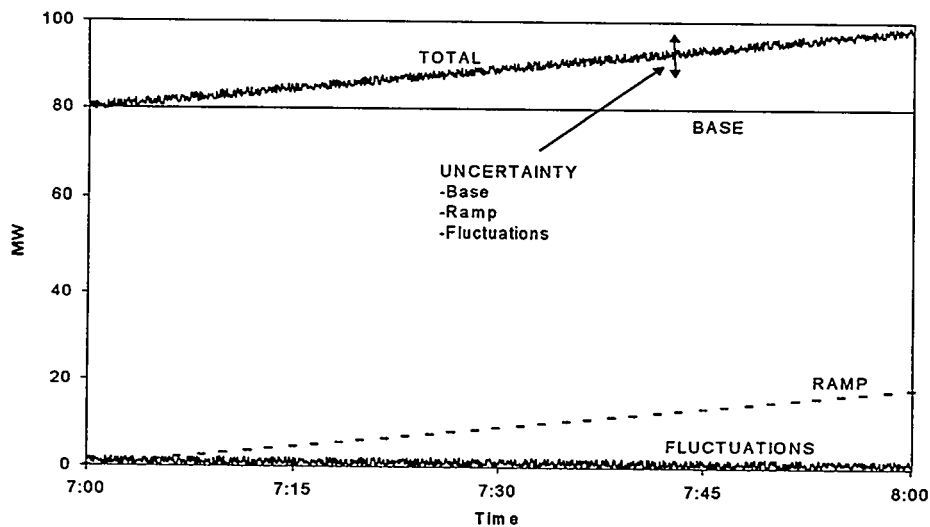


Figure 2 REGULATION COMPENSATES FOR FLUCTUATIONS IN LOAD OR GENERATION

Fluctuations in electric power generation magnitude and speed are relatively easy to measure. The inertia of the turbine is generally not sufficient to significantly smooth the power output in the 1-2 minute time frame of interest for regulation on a large interconnected system. Figure 3 shows the power output and wind speed for a single turbine at Esperance, Western Australia. *The Esperance wind plant is not representative of plants in the U.S. but it is one we were able to obtain high frequency power output data from.* The Esperance system is an isolated wind/diesel grid with nine V-27 turbines aligned in a row along the shore. This would tend to make the power highly correlated in the 1 to 10 minute interval. Still, Esperance is useful for this illustration. The coefficient of variation (COV is the ratio of the standard deviation to the mean and provides a normalized measure of variability) of this turbine's output is 0.88.

Two factors help reduce the adverse effects of this relatively high COV for an individual turbine. First, wind turbines themselves aggregate nicely into wind plants. Though individual turbines may have fairly high

fluctuations in output, each turbine tends to be relatively small (when compared to a fossil fired steam plant, for example) and numerous turbines are frequently combined to create a generating plant. But it is important to be sure that the turbines are uncorrelated over the time frame of interest. Rosser (1995) collected output data from each Esperance turbine at 1/4 second intervals and found that they aggregated as expected. The nine-turbine plant exhibits only 1/3 the fluctuations per KW of output as do the nine individual machines. When we examined the individual machine and aggregated plant output on a 10-minute basis, however, we found that the output from individual turbines was highly correlated and the plant output was only slightly improved when compared to individual turbine outputs, emphasizing the importance of ensuring that the fluctuations are uncorrelated in the time frame of interest. The shorter time frame is important to the application Rosser was investigating but when delivering power to the interconnected U.S. grid the time frame of interest for regulation is 1-2 minutes.

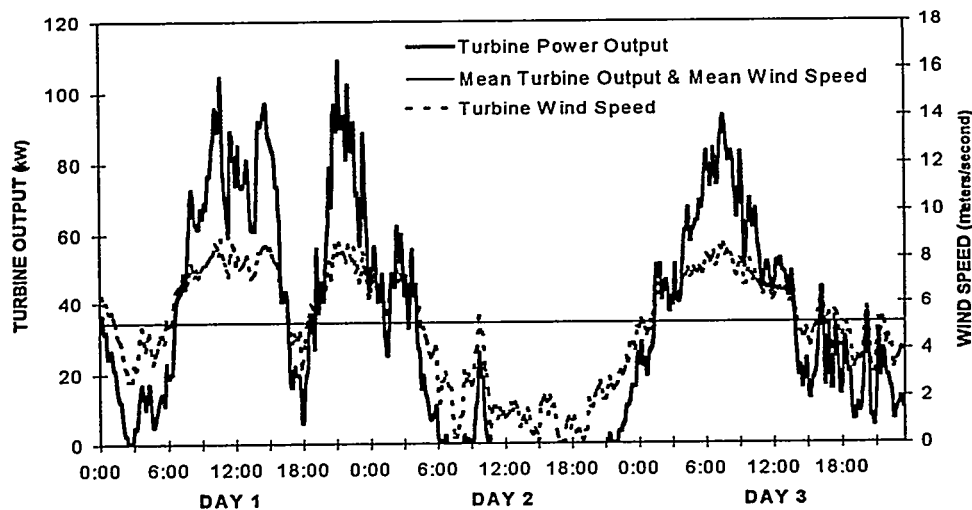


Figure 3 THREE DAYS OF WIND SPEED AND POWER OUTPUT DATA FOR A SINGLE TURBINE MEASURED AT 10-MINUTE INTERVALS

Second, suppliers of regulation will have different costs and presumably different prices. It may be worthwhile to utilize dynamic scheduling and shop for a regulation provider. It may also be possible to negotiate compensation for only the incremental impact on system regulation requirements, greatly reducing the cost.²

To get a feel for the regulation requirements of a larger wind plant (and implicitly the relative cost) we attempted to compare the regulation requirement of two wind plants in the western U.S. with the regulation requirement of a collection of non-regulating fossil fired steam plants. Unfortunately, data for the wind plants was not available at the more appropriate 1-minute interval and we were forced to use 3- and 5-minute data. Table 3 shows the standard deviation of the intra-hour fluctuations for three time intervals for each of the wind plants. The amount of regulating generation capacity required to compensate for intra-hour fluctuation is typically proportional to the standard deviation of the intra-hour fluctuations. Table 3 also shows the standard deviation if the wind plant is to make the same contribution to the regulation burden as a conventional thermal

²Unlike real losses, incremental regulation requirements get progressively lower as the system load increases. An individual would like to argue that it is only responsible for its incremental contribution to the aggregated regulating requirement (Hirst and Kirby 1996b).

plant.³ While these results are based on a very small set of data and require extensive additional investigation, they imply that, if restructuring requires that all generators pay for (or supply) regulating reserves to compensate for the burden they impose on the system, wind resources will be assessed between one and four times the requirements of conventional thermal generation.

Table 3 COMPARISON OF WIND PLANT AND NON-REGULATING FOSSIL STEAM PLANT INTRA-HOUR VARIABILITY

Case Description	Data Set Interval/ Duration	Average Power MW	Intra-Hour StDev MW	StDev to match Fossil Performance MW	Ratio of Wind to Fossil
10,500 MW Fossil generation	4hr/1min	10,500	33	33	1.0
200-MW Wind Plant	2.7hr/3min	179	4.5	4.3	1.0
	4.2hr/3min	80	3.5	2.9	1.2
	2.4hr/3min	68	4.4	2.7	1.6
1000-MW Wind Plant	19hr/5min	348	13	6.0	2.2
	12hr/5min	393	13	6.4	2.0
	10hr/5min	219	21	4.8	4.4

MITIGATION TECHNOLOGIES & STRATEGIES

Wind turbines and projects are generally optimized to maximize annual energy production in an effort to optimize profitability. In a restructured electric market it will be necessary to optimize across all revenues and all costs. There are a number of technologies and strategies that may help. The importance of each will depend upon factors specific to each wind project:

- o Re-Optimization of Wind Projects - The design of individual machines and of the integrated wind plant should be re-examined. One simple concept is to have a larger rotor and a smaller generator to maximize capacity factor. This would reduce power fluctuations because each turbine would be above rated capacity more of the time. An alternative would be to design a project with two sizes of turbines, the smaller of which could tolerate being stopped and started frequently, again minimizing fluctuations in electric power output. Pitch controlled rotors or variable speed generators might be preferred because of the added degree of control.

- o Geographical Diversity and Aggregation - As discussed above, aggregation is a powerful tool for reducing the regulation (and other) requirements. The larger the aggregation, both in numbers of generators and in geographic diversity, the greater the benefit. Dynamic scheduling may be useful to aggregate non-electrically-contiguous wind plants.

³Stated another way, this is the intra-hour standard deviation that N independent plants, each producing the stated average power, could each have if their aggregated output was to equal 10,500 MW with a standard deviation of 33 MW.

- o Variable-Speed and Solid-State Utility Interface - Variable-speed wind generation offers improved energy capture because the turbine can operate at peak performance longer. This should also reduce regulation requirements. Interfacing the wind turbine to the power system through a solid-state inverter gives additional control over the turbine real power output, helping to reduce power fluctuations. It also offers the ability to control reactive power independent of real power. The extent to which active control of real power delivery can be effectively utilized will depend on both the turbine design and the characteristics of the power system.

- o Array Control - Energy can be "traded" for reduced regulation burden by controlling turbine output (Javid, Younkins, and Hauth 1985). Control could be exercised over individual turbines or over the total wind plant to "spill" peak power, reducing undesired fluctuations. Curtailment or dumping of energy might be restricted to periods of rapid output rise and gusty conditions. It may be useful to tie this strategy to the new NERC control area performance standard which does not penalize control areas for over-generating when system frequency is low or under-generating when frequency is high. A control system designed to reduce fluctuations might be suppressed when the fluctuation is in a direction that will help restore system frequency, increasing the energy output of the wind plant.

- o Wind Forecasting - The DOE program ceased forecasting efforts in 1982 because of limited funding and a belief that techniques had gone as far as possible. Much has changed in the intervening time, including more rapid updating of mesoscale forecasts by the National Weather Service. Danish utilities ELSAM and ELKRAFT are forecasting their wind plant energy routinely. NREL has initiated a modest effort in forecasting wind for the 3 to 24 hour period. NREL will be seeking utility partners for validation in the near future. Wind power forecasting would also assist transmission planning and scheduling (Milligan, Miller, Chapman 1995).

- o Wind/Gas Hybrid projects - A wind project and a gas project could be operated jointly to take account of the best features of each with the gas-fired generation providing the rapid response required for control and wind extending the energy and possibly the capacity (Cadogan et al. 1992). Generation technologies other than gas, such as hydro, might be used if the economic and physical match is attractive. The hybrid might utilize dynamic scheduling to synchronize output if the projects were not co-located.

- o Short-term storage - A small amount of storage (perhaps 5 minutes of storage at 10 percent of rated wind plant power) could significantly reduce the regulating burden.

- o Dynamic scheduling - Dynamic scheduling can be used to electronically move the wind output to a control area where regulation is not as costly. Alternatively, dynamic scheduling can be used to facilitate multi-wind-plant aggregation or a hybrid system. It can also be used to aggregate the wind plant with a specific load, such as a municipal utility that prefers renewables and wishes to use the benefits of aggregating its load with the wind generation to reduce the overall cost of regulating the wind generation.

CONCLUSIONS

The U.S. electricity industry and its state and federal regulators are in the midst of a massive job of restructuring the industry. The future will be market-based rather than cost-of-service-based. We believe this trend will extend to the ancillary services. These changes will dramatically affect the opportunities for renewable resources such as wind that will compete either in the overall market or within a protected portion of the market.

In this paper we have begun to look at the implications of unbundling a single service: regulation. Each of the ancillary services has its unique concerns. A common feature is that actual minute-to-minute performance of both the renewable resource and the power system will determine the price of each of the services. Additional

research, especially involving collection of higher speed data from operating plants, is required to help the industry understand how wind can best participate in competitive markets. This will also help value advances in wind technology, further implementation of recent technical improvements, and help to direct future work.

Ancillary Service prices will depend upon the characteristics of the wind resource itself, the equipment employed at each turbine, the configuration and operation of the wind plant, the electrical characteristics of the interconnected power system, and the behavior of the power markets. Consequently, prices will vary substantially from project to project and from one time interval to the next. It will behoove project owners to pay careful attention to the governance of the power markets, individual contracts that are negotiated, real-time performance of the project, and the real-time performance of the markets.

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Slide 1

**Mechanisms for Promoting Renewables:
Theory and Practice**

**Nancy Rader
WINDPOWER '97**

Slide 2

Overview:

- I. Comparison of the RPS and SBC
- II. Overview of California SBC
- III. Comparison in Light of California Experience

Slide 3

Descriptions:

Systems Benefits Charge (SBC) —

- \$ collected via utility bills
- \$ allocated by state agency
- variety of allocation methods:
 - direct production incentives
 - grants
 - customer rebates
 - customer education
 - low-rate financing
 - "commercialization activities"

Slide 4

Descriptions . . .

Renewables Portfolio Standard (RPS) —

- Requires X% of power supply to be generated by renewables
- Applied to all retail sellers (or generators)
- Based on tradable "renewable energy credits" (RECs)
- Government role: certify and count RECs

Slide 5

6 Key RPS Issues to be Resolved Up Front

1. Define eligible renewables
2. Level of standard and rate of increase
3. Technology tiers
4. Cost containment - level of cap
5. Handling existing renewables: allocation RECs
6. At federal level: apply RPS to retailers or generators?

Slide 6

RPS & SBC: Similarities

1. Both support renewables in restructured industry
2. Both competitively neutral
3. Both recognize market imperfections and non-price benefits of renewables
4. Both mechanisms necessary in restructured markets —
SBC can support energy efficiency, R&D, commercialization
& low-income programs, but RPS more appropriate for renewables

Slide 7

	SBC & RPS: KEY DIFFERENCES	
	RENEWABLES PORTFOLIO STANDARD	SYSTEMS BENEFITS CHARGE
"The Debate"	Sustainable path: Whether and how much to increase renewable energy	Price tag: How much money to spend on renewables
Up-front Design	Somewhat complex: 5 key issues must be resolved	Simple: set level of tax
Results	Defined: % of total supply = renewables	Depends on implementation
Total Cost	Market determines. Expected cost < Cost cap	Precisely defined
Government Manages Fund?	No	Yes
Public Implementation	Simple: certify and count credits	Complex: How to spend \$ is political, contentious and ongoing
Who chooses winners?	Market seeks least-cost, greatest value technologies & applications	Politicians, regulators, and administrative rules
Pressure to reduce costs	Continuous — on both retailers and renewable generators.	One-time competition for funds. Pressure only on renewables.
Market push or pull	Pull: creates a market for renewables	Push: no market created
Effect on Federal PTC	Does not affect	Many methods reduce PTC (and ITC)
Sunset	Automatically phased out when credit price falls to zero	Arbitrarily and politically determined
Money Well Spent?	Yes, if you believe in competition	Yes, if you believe in politicians and administrators

Slide 8

CEC Recommendations for Expenditure of SBC Renewables Fund Total Fund = \$465 - \$540 million			
	% of Total Fund (4-year avg)	Average 4-year per-kWh production incentive (est.)	Notes
Existing	45%		Target Price & Caps
Tier I Biomass, Solar Thermal, MSW	25%	0.90 ¢/kWh	T = 5.0¢ declining to 3.5¢ Cap = 1.5¢ declining to 1.0¢
Tier II Wind	13%	0.67 ¢/kWh	T = 3.5¢ Cap = 1.0¢
Tier III Geothermal, Landfill gas, digester gas, small hydro	7%	0.13 ¢/kWh	T = 2.5¢ Cap = 1.0¢
New - Total	30%	Determined by auction	Production Incentive. Cap = 1.5¢ paid for 5 years Limit 25% per bidder
Emerging	10%		No cap
"Customer Rebates"	15%	Variable	Cap = 1.5¢
Customer Education	1%	n/a	

Slide 9

	CALIFORNIA SBC VS. PROPOSED RPS	
	PROPOSED RPS	ACTUAL SBC
Up-front Design	10% non-hydro standard, rising 0.2% per year for 5 years 1.8% biomass tier Existing generators get RECs	Level of tax = 0.70% 1998-2001 No less than 40% for existing and 40% for new/emerging
Results	Defined: 10% of total supply = renewables	Uncertain. Decline in total renewables likely.
Total Cost	Market determines. Expected cost < Cost cap Est. bill impact: 37¢-\$1.25/month	Precisely defined: \$465-\$540 million ≈ 50¢/ household monthly bill
Government Manages Fund?	No	Yes - California Energy Commission will manage funds for 5 different programs
Public Implementation	Certify and count credits	6-month process at CEC + legislative review. Pits allies against each other.
Who chooses winners?	Market: Head-on competition between existing and new. Unhindered competition between renewables technologies.	CEC, legislators and rules Examples: -- 40/40 split -- repower ≠ new under contract -- no repowers <u>bid</u> under contract?? -- 25% per bidder limit for new \$ -- threshold criteria for bidding
Pressure to reduce costs	Continuous — on both retailers and renewable generators.	No competition for existing & consumer rebates. One-time competition for new and emerging.
Effect on PTC	Does not affect	Unclear
Sunset	Automatic when renewables competitive	SBC ends in 2001.
Money Well Spent?	Yes, if you believe in market competition	Very debatable. Examples: -- ramp-down of wind funds -- Tier III funds -- uncertain rebate -- new project cap; milestones -- annual appropriation uncertainty?

A VIEW FROM MINNESOTA: A CHANGING CLIMATE FOR WIND POWER

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CLIMATE CHAOS: IS THE PUBLIC ABOUT TO CATCH ON?

The director of the NASA's Goddard Institute, James Hansen said in *Newsweek* in January 1996 that "the climate system is being pushed hard enough that change will become obvious to the man on the street within the decade." To corroborate the statement, I contacted Robert Watson, who was then the White House Science Policy Advisor and is now the new chair of the International Panel on Climate Change. I asked Watson if he thought that Hansen's statement was reasonable. He said that he would not make such a statement since it cannot be proven, but that Hansen is within the mainstream of climate science and that he may well be right.

I often quote this statement, not for what it says about the climate, but what it says about the potential for public opinion snapping into focus that we have a big problem on our hands. It is my belief that it is not green marketing that will vastly expand the opportunity for wind energy, but the fact that the public will insist upon carbon-free energy for everyone once they realize the seriousness of the climate problem.

As many of you who follow the climate issue know, the U.S. has been no world leader on addressing the problem, largely because of the enormous political power of the fossil fuel industry as exercised in states like Texas, Louisiana, Oklahoma, Alaska, West Virginia, Ohio, Indiana, and North Dakota. Americans have begun to identify the corrosive power of money in elections and American politics, and the oil, coal and gas industries are no exception. Fossil industries contributed ten million dollars to Congressional races in the past three years, reaping \$4 billion in special tax breaks during the same period. The failure of the Administration to lead on the problem of the global climate has been especially painful for the environmental community, because as Vice President Gore is fond of saying, he wrote the book on global warming back in 1991.

Sixty days ago, all of America watched on the nightly news the destruction of one of the economic hubs of the State of North Dakota, the city of Grand Forks, as well as several smaller Minnesota communities. After Vice President Gore visited the flood-ravaged communities, an op-ed by Carleton College professor Dale Jamieson took him to task for failing to mention the potential connection between global warming and the catastrophic flooding of the Red River Valley communities. After all, Fargo received exactly ten feet of snow this winter, breaking the all-time record of seven and a half feet, and smashing the average annual snowfall of a little more than three feet. An unusually warm spring string of weather created a rapid snow melt.

Then a final blizzard and a hard freeze hit just as the waters were cresting in the towns upstream of Grand Forks. President Clinton visited the destroyed city on Earth Day. Clinton acknowledged that many scientists believe that the increasing frequency of severe weather events such as floods, droughts, extreme rainfalls, extreme snowfalls, extreme heat and cold, are the early signs of global climate change. He was perhaps referring to research in 1995 by Dr. Thomas Karl of the Climatic Data Center of the National Oceanic and Atmospheric Administration. Karl's team of researchers verified the increase in severe weather events in China, the U.S. and the former Soviet Union and they assigned a probability of 90% that the increase in these events is caused by human-induced changes to the climate. Clinton's exact words rang through the fossil industry and the environmental community. Though cautiously couched his statement in scientific caveat, what he, in effect, said was 'Folks, this is probably global warming.' To my knowledge, this was Clinton's first mention of the climate problem in any public forum in the U.S. except for a statement during this year's State of the Union Address that we must reduce greenhouse gases and that we are changing the climate. Subsequently, he again spoke of the problem while visiting Costa Rica and then last Thursday he made extensive comments addressing the Business Roundtable in Washington from which I will quote in a few moments.

In an ironic twist of history, the public interest community in Minnesota spent the past five years fighting with the State of North Dakota, the coal industry and all Minnesota utilities trying to get a economic quantification of the costs of environmental damages from electric generation. For many reasons, the contested proceedings heavily focused on carbon dioxide emissions and global warming. In a decision described as conservative by the Minnesota Public Utilities Commission in December 1996, the cost of current emissions from Minnesota alone leaves our children a debt in environmental damage of between \$1 billion and \$6.5 billion each year. In the end, activists realized that many of the risks of climate change were not readily quantifiable in market terms. For example, how do you value species extinction, as habitats and ecological communities are torn asunder by rising temperatures or declining precipitation. Next week for example, our coalition is joining with the World Wildlife Fund to do a national release of report on what ecologists believe that climate change will do to our National Parks. Minnesota's own Boundary Waters Canoe Area Wilderness and Voyageurs National Park are expected to suffer massive deaths of the spruce and pine forests, because we are at the southernmost edge of their ecological range, and warming is expected to begin moving the boundary of the boreal forests northward in as soon as twelve years. Even if such precious resources as Minnesota's wilderness habitat were quantifiable in economic terms, these externality cost estimates were intended to be used in integrated resource planning, and as everyone knows, the idea of resource planning has passed its fashion hey-day, and the new wave is green marketing.

Rather than join the fashion bandwagon to promote green consumers, the coalition that I represent is recommitting itself to its roots. Our job is not to build a green consumer base for the new market, our job is to build a base of green citizenry to speak up about what they know in their heart to be true.

BUILDING A GREEN CITIZENSHIP IN MINNESOTA

What is the Minnesota public interest and environmental community doing to help build a green citizenry to advance renewables? We invite you to come learn about our work on the internet at www.me3.org, It's one of the best web sites around.

To start with, like all good companies, we are listening to our customers through our own polls and research. We learned for example what values are important to average Minnesota citizens in the coming debate about restructuring of the electric industry. Using an research tool called a Citizen Jury_ administered by the Minneapolis-based Jefferson Center, a jury panel representing a statistically valid cross-section of Minnesotans listened to a balanced array of expert opinion on restructuring the electric industry, and decided that reliability and environmental protection were there highest priorities, substantially higher than either price or choice.

A good Minnesota example of the power of green citizenship is the 1994 legislative decision that the state's largest utility should diversify its resource portfolio as a way to reduce its reliance on nuclear power. The famed Minnesota mandate of 425 megawatts of wind power and 125 megawatts of biomass energy is a good example of the power of a green citizenship. Acting in their capacity as citizen leaders, the Minnesota legislature put Minnesota at the lead of the domestic wind industry: when fully installed, the 425 MW will cost the average Minnesota household about 35 cents a month.

Let's contrast that with experiences elsewhere: in Texas, Central and Southwest did extensive polling and found that 80% of its customers would be willing to pay \$1 a month extra for renewable energy. Instead of building it and providing 80% of the customers what they want, CSW instead responded to the 20% who don't want it, which presumably includes the industrial customers. Now, a few customers who will actually shell out a minimum of \$4.50 per month can participate in acquiring new renewables. Of course, the utility believes it cannot voluntarily reduce its competitiveness by adding renewables to its bundled resource mix, even though 80% of the customers support it. It seems that even utilities which are directly owned by members or directly accountable to municipal or public constituencies are missing the opportunity to respond to the expressed preferences of their customers. The arithmetic is compelling: if a majority favor renewable energy they should exercise their authority as citizens rather than as consumers. That way, they will get more renewables at a lower cost. If the utility is cooperatively- or publicly-owned, the members can vote to require their utility to develop "green citizen power" programs. When a utility is investor-owned, the avenue is more indirect through the legislature, as with the Minnesota mandate, the Iowa purchase requirement, and the merging discussion of renewable portfolio standards.

When considered against the backdrop of the climate problem, the argument that only some residential customer will choose green power and commercial and industrial customers can opt out does not hold up. Renewable energy's public benefit is not a luxury: it is a need driven by the physics of the atmosphere. Paraphrasing environmental writer Bill McKibben: "When the laws of economics and the laws of nature are in conflict, the laws of nature are not likely to yield."

Other Minnesota institutions are playing key educational roles in promoting green citizenship. The Science Museum of Minnesota has a fantastic wind exhibit. They are here today with parts of their exhibit that ties modern wind power back to its agrarian roots, as it looks to a future of decentralized and locally-controlled energy sources.

The Sustainable Resources Center has been supported for an additional two years by the State legislature to assist small companies, farmers, and local communities evaluate wind energy as a business opportunity. An excellent curriculum project has been developed and it has been well-received by farmers who are used to working with commodity prices that guarantee they lose money. One of our rural renewable leaders jokes that "I inherited Dad's farm that's worth a million dollars and I love farming so much I'm gonna farm until it's all gone."

In 1997, rural legislators took the lead in new legislation expanding eligibility for a unique Minnesota producer payment incentive going to projects less than 2 MW — the program offers 1.5¢ per kilowatt hour for ten years to qualified small businesses, non-profits and Indian tribes.

Our coalition is organizing a statewide campaign in favor of a shift in the taxes that Minnesotans pay — reducing taxes on jobs and income and offsetting those taxes with pollution taxes based on carbon emissions. Analysis by the Tellus institute last year demonstrates that this policy would have a modest stimulating effect on Minnesota's economy overall, and give us leadership opportunities in developing markets for the environmental technologies of the future.

In addition, we are building networks and media outlets to get information to the public on the changing climate. We are creating a public conversation about the problem and how it will affect the quality of life that Minnesotans enjoy. We are focusing on getting out the research being done that shows that many of the resources that we cherish, which people in our state consider their birthright, are at serious risk of being lost or severely depleted in their children's lifetimes.

In Minnesota, massive death of forests will result with a two degree Celsius increase in temperature. Models show large percentages of prairie wetlands will be lost, putting increase pressure on stressed waterfowl species. A lake ecologist at the University of Minnesota has modeled a 40% reduction in populations of cool-water game fish which currently support an \$850 million dollar fishing and tourism industry. One in four Minnesotans buy a fishing license and spend time fishing with their friends, their children and their grandchildren.

It will take months or years for families to heal from the loss of security and the financial losses from this spring's flooding. While it cannot be stated certainly that the changing climate is the cause, as the Vice President said recently in a Minneapolis op-ed, increased flooding is "consistent with the predicted effects." Now, barely catching our breaths, Minnesotans are fearing a summer drought following one of the driest springs on record.

WANTED: AN ENERGY SYSTEM OUR CHILDREN CAN LIVE WITH

James Hansen appears to have been right: the people of Minnesota may be slowly catching on that something is already amiss with the climate. Whether you believe that people in your

region are beginning to see the connection between anomalous weather events and global warming, or you doubt very much that a changing climate will ever be perceptible to the average observer, I strongly advise those involved in the wind industry to read Ross Gelbspan's new book on the subject: *The Heat Is On: The High Stakes Battle Over Earth's Threatened Climate*. When the Pulitzer Prize-winning reporter spoke last month at a Town Meeting we hosted in Saint Paul, he laid out what the scientists know, what they think they know and what they are unsure of. He showed how the fossil industry has succeeded in keeping the public confused with a well-orchestrated campaign of disinformation, led by a handful of scientists who form the thin right edge of the bell curve of climate opinion. Gelbspan shocked the audience with a matter-of-fact statement calling for the phase-out of fossil fuels in a decade in an all-out effort comparable only to mobilization for the Second World War, reminding the audience that the politicians and the climate negotiators cannot admit that the emperor is wearing no clothes. The International Panel on Climate Change says that a 60 to 80% reduction will stabilize the climate, but reporter Gelbspan is asking the reader whether a 60 to 80% reduction will be sufficient if the current status is a highly unstable imbalance?

Tomorrow, five national environmental groups are releasing a new report entitled *Energy Innovations: A Prosperous Path to a Clean Environment*. Their "Innovation" scenario does not meet Gelbspan's timeline, but models the end of coal and nuclear for the generation of electricity by the year 2030. The U.S. has a \$500 billion annual energy bill, and although the U.S. market for wind is very weak, the world market added 1200 MW this year and 1200 MW last year. There is no reason why the U.S. should not be adding 1200 MW a year on its own. It will not be green marketing that causes that to happen as likely as it will be a policy decision in response to an insistent public that the U.S. show the leadership needed on the central environmental problem of the coming century.

My message is simple: a green fraction of residential consumers cannot sustain and move forward the wind energy industry to where it needs to be for the sake of the planet. Public policy leadership is more important than access to markets, or a hefty green marketing budget. Industrial and commercial customers cannot opt out of an obligation to squarely confront the problem of the changing climate. After a flurry of anti-environmental advertising last week by the Business Roundtable, an association of CEOs of America's largest corporations, President Clinton addressed them this past Thursday, and saved his closing remarks for an admonition on climate change.

I was very moved by the speech recently given by the Chairman of British Petroleum on the issue of climate change. I don't know how many of you read it, but essentially what he said is, look, nobody knows exactly what the impact of climate change is, but let's not deny anymore that the climate is changing and that it can't be good, and that no harm will be done if we take sensible steps to try to reduce greenhouse gas emissions and to do other things which will help us to preserve the environment.

We've had more extreme weather conditions in the United States in the last five years than we had in the previous 30. And we know from all the scientific studies what is happening to the temperature of the globe. What I ask you to do is to work with me in good faith to give our children a world worth living in.

A lot of you have made a good deal of money in your corporations by technologies which improve the environment. And if we have the strongest economy in the world, we will find a sensible way to grow that economy in a way that fulfills our responsibilities. Today, with 4 percent of the world's population, we produce over 20 percent of the greenhouse gases. We're up 13 percent since 1990 when President Bush and his administration said we would try to hold constant through the year 2000.... I do believe it is folly for us to believe that we can go into the next century without a strategy that says we're going to be responsible and we're going to do our part and lead the world on the environmental issues -- because we all know what the evidence is.

I invite you to think of the wind industry role in the battle that will be waged over the climate. Perhaps you are in this work because you want to leave a secure world for your children. Your neighbors and the people you see on the street want the same thing. And when they learn the truth about the problem that we are saddling our children with, public opinion will snap into focus and serious change will begin. Americans will soon agree that we should tackle this climate problem, and it is the job of the wind energy industry to be ready to do its part, and to help develop the conditions to help make that paradigm shift possible.

Changing Market for Renewable Energy in New England

Mike Jacobs
Second Wind Inc.

Windpower '97
June 16, 1997
Austin, Texas

In the 6 New England states, legislators and regulators, buyers and sellers all lining up to include some renewable energy in the restructured electricity market. How much, and how soon are not clear. How this is developing is subject to some argument, but consider these facts:

- Deregulation in New England came quickly, perhaps in two years of regulatory debate and just one year of legislative debate.
- Utilities, the players with the most ability to do wind in the region, have been convinced, to the surprise of many, that they are better off selling all of their generation assets, and exiting the energy production business. This by definition removes them from the list of possible developers or purchasers of wind energy.
- Marketers and brokers are only now appearing, as there are only a small number of retail buyers that can be contested or won in the market before 1998.
- Of the marketers and brokers, many are trying to offer green energy products, some of them on the podium beside me.

The marketers and brokers are seeking green credentials, testing the green market, defining themselves as green, and clearly learning as they go. There is a legitimate question in the market as to what the green energy products are offering in the way of new renewable energy facilities.

My main subject is the imbalance between the demand for green energy, and the ability of the active market players to provide it. I suspect that part of the problem is a learning curve, or a market failure, or whatever you wish to call it, while the players talking about renewable energy are largely marketers and brokers that do not fully know their own, very new retail electricity business, let alone the business of buying, or building, windpower. In a market that has not yet opened beyond tiny experiments, the retailing of green power in New England is still 6 months away.

In 4 of the 6 new England states, the legislature has proposed or enacted significant RE policies, ranging from bona fide RPS in Maine to SBC in Rhode Island. The atmosphere in the region favors SBC, and this conference and the AWEA would do well to form a

position about how to use a fund from an SBC in the various states that are not equipped with California windfarms.

Renewable Electricity Policies in the New England States

Maine	Renewables Portfolio Standard
Vermont	Renewables Portfolio Standard
Rhode Island	System Benefits Charge to support DSM and RE
Massachusetts	System Benefits Charge to support RE, Fuel Source Labeling
New Hampshire	Retail Competition, without policy on Renewable Energy
Connecticut	No decision on Retail Competition

The Massachusetts policy-making has been the most detailed and lengthy. The Department of Public Utilities issued proposed rules for competition, which included a System Benefits Charge of 1 mil per kWh sold in the state to assist in the commercialization of new, renewable technologies for generation. Six months later, the DPU confirmed this as its proposal, but deferred implementation to the Legislature, illustrating the serious nature of the jurisdictional confusion in the re-writing of utility law. The DPU also accepted the notion that a collaborative discussion should advise the DPU regarding the spending of the money collected for renewable energy support. A similar process was used invented in Massachusetts for efficiency investments with ratepayer funds.

The Massachusetts Legislature was moving towards deregulation at the same time, and had created a special committee to explore retail competition. The work of the committee led to a bill with convincing momentum. In the Legislature, 100 bills are circulating that affect utility law at this time. Enactment of something is expected in a matter of weeks.

The process in Massachusetts has turned to a series of collaborative meetings to define what might be done with \$40 Million collected each year for renewable energy, assuming final enactment of leading proposals from legislative and regulatory commissions. This collaborative process is the third place where the definition of renewable energy has been debated.

We also saw public jousting by different branches of government over sponsorship of collaborative meetings. Then a late start was made. The first full meeting was just that, FULL. A standing room only crowd of professionals; lawyers, utilities, marketers, manufacturers, developers, government and NGO's volunteered to participate in shaping RE policy in Massachusetts and the expenditure of the \$40 M.

This process may not be repeated in numerous states, thankfully, because it is very time consuming and demands expertise on all sides of the debate. Still, the central questions of a system benefits charge will appear in each state that adopts such a tool to promote renewable energy. In Mass, this month, the questions can be framed as follows:

1. How will RE be defined? - an annoying question for us in windpower, but a vital one for the trash burners, conventional hydros, and in our political stew, the fuel cell industry using pipeline gas.
2. Is the fund for domestic projects and kWh, or something more abstract? - There is pressure for providing capital to local firms that will expand their RE capability, even if the generation is installed in overseas markets where the valuation of RE is higher. With this approach, the fund may benefit from more lucrative markets overseas, but the domestic market for wind certainly won't do as well.

As this debate reaches climax in Massachusetts and arises in other states, wind advocates need to choose their positions and allies that will agree on the best approach for windpower.

After the political and legal debates are finished, the marketplace takes a central role. Key will be the buyers and sellers.

Buyers and Sellers:

I made reference to the interest of marketers in green pricing. The Massachusetts Electric Pilot explicitly grouped the offerings of all the sellers in the program as characterized as either based on price, environmental attributes, or "other", which were price hedging approaches.

The other papers presented in this panel describe the details of New England retail pilots, but I would like to generalize the results for the residential sector. The dominant decision in the pilots was to do nothing. The next most popular choice was some sort of package that was labeled "Green" and priced higher than the other choices. This has served as evidence that customers can be attracted to the green product.

Shifting to the supply scenarios, let me describe a spectrum of sources ranging from the wind projects to the less desired renewable energy choices, to cheap gas. The larger supply and demand picture is not what it used to be in New England.

Starting with green projects, there are not as many projects, wind or other RE, proposed for permits in the Northeast as in other regions. The two most promising proposed projects are in the Boundary Mountains of Maine, for which Kenetech had won a permit for 200 MW, but lost the 20 MW contract and everything else. Zond recently bought the rights to the project. The second is a long-awaited RFP for 6 MW on Nantucket Island, that most do not want to release for fear of the siting battles, regardless of site selection.

The island is an exclusive summer resort with more capabilities to fight a project at the local level than any I can imagine. The only wind project to move forward is the 6 MW Green Mountain Power project in southern Vermont and western Massachusetts.

Next is Canadian hydro, primarily Hydro-Qubec. Imports exceed 1800 MW or roughly 10 % of New England's annual usage. The capacity to deliver is limited by grid stability in the eastern US, because a single DC line capable of delivering 2000 MW throws the region out of balance when it drops off suddenly. Discussions of increased imports, and new hydro development, including the planned catastrophe known as Grand Whale and another land grabber in Labrador have Canadian interests very excited about the market in New England.

New England is demonstrating that deregulation and competition places a great deal up for grabs. 1,2,3 nuclear units have already been retired, and practically the rest are under scrutiny, or closed for repairs, and not likely to last as long as planned. This creates roughly 3000 MW of unmet capacity need in a region of less than 30,000 MW. Capacity prices have climbed steeply due to the temporary and permanent nuclear plant closures.

Further plant closures are predicted among the fossil-fired units. The conventional wisdom sees the market price for bulk power is the price of modern combined cycle gas units in the 300 MW scale. Several are in the permitting process, with more on the drawing boards straddling new gas pipelines. Recognizing this, one proposal in a recent power plant auction explicitly promised to buy old plants **SO AS** to retire them. This is a joint venture between the leading regional environmental lobbyist, Conservation Law Foundation, and powerplant developer AES. CLF gets cleaner air, and AES gets prime real estate for new plant construction. No word yet on the outcome of the proposal, but it was front page news in the Boston papers when the proposal emerged.

This picture is necessarily a work in progress, as these presentations often are. However, this is an open market, and many more wind projects can participate in this market. The retail sellers seem to think wind and renewables have added value. Government policy, also still unfinished, is attempting to promote renewables with funds or market portfolio standards. The customers are likely to be the final arbiters, and both the sellers and the elected sense there better be a green tint to the restructured electricity market in New England. It is my opinion that there is a shortage of wind projects at this time in a market that has more demand than supply. Whether that demand is cultivated, or filled by technologies this audience would call an impostor, is an open question. The outcome will be influenced by the actions of the wind industry. We hope that there will be market-driven windpower activity that can capture the interest in the region.

GREEN ELECTRICITY: TRACKING SYSTEMS FOR ENVIRONMENTAL DISCLOSURE

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INTRODUCTION AND SUMMARY

For the first time, electricity consumers in the US are beginning to choose their generation providers. One of the opportunities created by the introduction of retail choice in electricity is the chance for customers to influence the mix of generating resources through their purchasing decisions. Some environmentally aware consumers will want "clean," "green," or renewable power. While some suppliers will attempt to differentiate themselves according to their environmental performance, such claims for green electricity can be particularly difficult to verify given the complexity of the interconnected electric system.

Because electricity is delivered over an integrated transmission grid and kilowatt-hours at the point of retail sale are indistinguishable from each other; disclosure requires tracking protocols to attribute generation at power plants to sales at the customers' meters. Fortunately, it is possible to implement a workable disclosure system. Some states have already included disclosure requirements in their electric industry restructuring orders and legislation (see Massachusetts DPU, 1996; Vermont PSB, 1996; Maine legislature, 1997). In this paper, a set of design criteria for an environmental disclosure system are presented along with two methods for disclosure: the company approach and the product approach. In addition, we discuss of power pools, data availability issues, and propose a company-based disclosure system using a "wholesale sales first" approach to transaction accounting.

WHAT'S SPECIAL ABOUT ELECTRICITY?

There are several reasons that policies beyond standard consumer protection and truth-in-advertising might be appropriate for electricity. First is the scale of the environmental impacts -- for example, the carbon dioxide emissions from power plants amount to more than one third of the U.S. total (EIA, 1996). Second, there is the fact that the environmental benefits of "green" electricity are not characteristics of the product itself at the point of retail sale, but rather have to do with the nature of its production at the power plant. Finally, and perhaps most importantly, there is the complexity of the transmission grid and power markets, making unambiguous *physical* determination of the source of a particular kWh impossible in most cases.

An important objective in electricity restructuring is the creation of an efficient market in which retail customers have meaningful choice. One condition necessary for an efficient market is the availability of complete and accurate information to customers. The challenge for policy makers, advocates and industry is to develop a workable system for environmental disclosure so that customers, especially those who are willing to pay more for "clean" electricity, can actually influence the resource mix in a meaningful way. The conclusion of this paper is that it is possible to implement a meaningful and useful system of environmental disclosure, but that it must be based upon the organizations involved in the production and sale of electricity, and the transactions between them.

TRACKING ELECTRONS: IS IT POSSIBLE?

Given the physical reality of electricity production, it is not possible to determine “which electrons go where” (it is worth noting that electrons do not move *along* the wires of an alternating current system). Within the framework of an interconnected grid, it is also not possible to determine the source and recipient of a particular electric flow, much as is true for the water in a reservoir. However, tracking *responsibility* for electricity from generation to point of retail sale is necessary for a working electricity market – every kWh generated is produced with an expectation that someone is going to pay for it. There are different ways that such tracking can be done; what is important is that a consistent approach be adopted and implemented over a fairly broad geographical region. While electricity markets can be created without tracking fuel mix and air emissions, meaningful customer choice requires full disclosure. This requirement was recognized in a recent resolution by the National Association of Regulatory Utility Commissioners, which “urges states adopting retail direct access programs to include enforceable standards of disclosure and labeling that would allow retail customers easily to compare the price, price variability, resource mix, and environmental characteristics of their electricity purchases.” (NARUC, 1996)

TRACKING TRANSACTIONS: IS IT NECESSARY?

Despite the ambiguity of the physical movement of power, it is nonetheless entirely feasible to create a system in which responsibility for generation and its environmental impacts is attributed to retail sales in an unambiguous way. Indeed, such a system will be necessary in order for “green marketing” to be meaningful. Moreover, many systems of accountability are already in place. Natural gas pipelines and electric power pools are good examples.

Natural gas pipelines have developed systems to keep track of entitlements to various services and deliveries into and out of the systems. These do not attempt to track specific gas molecules. Rather, they track transactions for operational and billing purposes.

DESIGN CRITERIA

It is often useful to begin with specific objectives. What are the characteristics that an environmental disclosure system should meet? The following is a list of design objectives that deserve consideration.

1. Effective: It should make a difference.
2. Accurate: It should give consumers good information about the sources of their electricity.
3. Comprehensive: It should allow for disclosure of a wide range of environmental impacts, and fuel-type information.
4. Flexible: It should encourage innovation in technology, contracting and marketing.
5. Simple: It should be straightforward and readily understandable.
6. Expandable: It should work at various scales so that it can start small and grow geographically.
7. Inclusive: It should provide opportunities for existing utilities and new players to offer green products.
8. Credible: It must be trustworthy initially and over time. To the extent that the system embodies subjective value judgments, they must be made by a squeaky clean process involving reputable individuals and organizations.

These criteria depend on each other and can in some ways conflict with each other. For example, the ultimate objective may be to develop an effective system, one in which consumer choices have the

desired impact on the market and this requires that disclosure be accurate. However, the simplest system will not be the most comprehensive and the most flexible may not be the most credible.

Different individuals and organizations will give more or less weight to each of the objectives, possibly leading to very different views of how the disclosure system should work.

WHAT TO DISCLOSE?

Analyses of the environmental impacts of electricity production can -- and do -- fill volumes. Some recent studies that attempt a comprehensive scope include the DOE's *US-EC Fuel Cycle Study* (ORNL and RFF, 1992), the *New York State Environmental Externalities Cost Study* (RCG/Hagler, Bailly, Inc. and Tellus Institute, 1994) and the Boston Edison Settlement Board's survey of the benefits of energy efficiency programs (Biewald, et. al., 1994).

From an environmental perspective, the most fundamental attribute of an electricity supply portfolio is probably the fuel mix. The fuel information implies -- albeit somewhat imprecisely -- information about resource depletion and the broad categories of environmental and health damages. For example, coal generation in the mix implies carbon dioxide emissions. Nuclear generation implies radioactive waste. The magnitudes of the contribution to global climate change or to the country's radioactive waste disposal task are not conveyed directly by the fuel mix -- but it is a start.

It is possible also to present information on key air emissions (e.g., carbon dioxide, particulates, nitrogen oxides and sulfur oxides) and radioactive waste. To be most meaningful, these could be presented on a scale relating them to the U.S. average for electricity supply.

Disclosure could also be taken a step further, presenting estimates of the impacts themselves rather than the emissions or environmental loadings. For example, the number of deaths per kWh can be estimated for power plants on a generic or site-specific basis. This would undoubtedly be controversial.

One of the tensions in deciding what to disclose is the role of value judgments. The idea that there are good and bad -- or better and worse -- resources underlies the basic purpose of disclosure. However, a disclosure system can attempt to stick strictly to "the facts" or it can venture into the subjective ranking of resources against each other. It makes sense that a mandatory disclosure system would aim to be based upon measurable and objectively relevant data while a voluntary system (or an environmental rating system designed and implemented by an independent organization) might tread further into the difficult but useful realm of subjective comparison.

Some of the trickier decisions might have to do with whether specific resources are classified as "renewable" -- debates about waste-to-energy facilities and hydro-electric facilities have been particularly contentious. Even a system that attempts to be "neutral" will embody some value judgments in the determination of which facts to include.

Ultimately, both the level of detail and the aspiration to objectivity must strike a balance. With too much detail suppliers will be burdened and consumers will be overwhelmed; with too little the system will be inadequate to meet its objectives. With too much subjective valuation the system will be open to criticism and will run counter to some of the varied values of individual consumers. If a strict standard of having a system that is entirely "value-free" is adopted, then very little useful information can be communicated.

COMMUNICATION MODES

The information can be disclosed in various formats and through various channels. The format for disclosure should probably follow the example of nutritional labeling: a straightforward standardized layout using percentages and relating technical information to commonly understood benchmarks. Research is currently underway to determine what information electricity consumers will want and be able to process (Levy et al, 1997).

The vehicle for disclosure should include the bills that are sent to customers and the promotional materials that suppliers develop for marketing. The roles for industry, government and others need to be worked out. At one extreme, a disclosure system could conceivably be entirely voluntary, designed and implemented by the market participants. At the other extreme, government agencies could undertake the bulk of the activities themselves -- collecting data, calculating attributes, verifying and enforcing the system. Another model would rely upon independent parties to rate suppliers -- along the lines of "Consumer Reports."

The most successful approaches will probably draw upon all of these actors. The minimum role for suppliers would involve making the essential data (primarily quantities of energy transactions) available. Independent third-party rating systems are likely to develop in one form or another on their own accord. Government can take the role of outlining information requirements for industry to comply with, and then to spot check on disclosure accuracy.

DISTINCTION BETWEEN OLD AND NEW RESOURCES

Incremental change in the electric resource mix -- related to design criteria number 1 above -- will primarily be a matter of new plant construction. That is, if green consumers simply get existing "clean" resources allocated to them then changes to the system mix, if any, will be very gradual in coming. Some astute green consumers may demand that any clean power that they are paying extra for be verifiably incremental to what would have been done anyway.

Verification that something is incremental can be difficult, and inevitably depends upon a hypothetical projection representing the baseline case. One simple approach to cutting through this difficulty is to make the assumption that anything new represents incremental progress. A system might make this distinction based upon the date of first operation. For example, resources that went into commercial operation after the date of opening electricity markets to retail choice might be afforded special status in a disclosure system.

TIMING AND ACCURACY

Timing is everything. With disclosure, there is first the issue of how frequently the information should be put in front of the customer. This issue should be researched along with the design of electricity labels.

A separate issue is the matter of time period for doing any calculations. For example, a system that tracks transactions on an hourly basis will give a different result than one based on annual averages. It may be that quarterly estimates provide the right balance between accuracy and burden.

Finally, there is the timing issue of prospective versus retrospective information. A disclosure system might base information on recent history, adjusted for major expected changes such as the expiration of a contract or a major plant outage. Utility rate cases often use actual data for a "test year," and then adjust

it for "known and measurable changes." Perhaps an analogous approach could be developed for electricity disclosure. Alternatively, it may be preferable to use an approach with true-ups, where the information reported would be reconciled with actuals over time.

The level of accuracy required of the tracking and disclosure system depends on the purpose. For example, if the tracking is to support labeling then a high degree of accuracy may not be necessary, while tracking to support an emissions portfolio standard would require a very high degree of accuracy (and hence, true-ups).

DISCLOSURE FOR PRODUCTS OR COMPANIES?

Disclosure systems can be based upon companies or products. With a company approach, the attributes of all the resources of a company are disclosed to all of its customers. With a product approach, particular resources may be allocated to particular customers.

The product approach would allow a company's renewable resources to be "sold" to customers who are willing to pay more for them. This system also provides for situations in which customers want to buy from a particular local generating plant. It also allows companies to creatively design portfolios or products to offer to various customer groups. However, the disadvantages of product disclosure are enormous -- particularly with regard to the objective that green consumers "make a difference." If *existing* renewable or clean generation is simply allocated to those customers who are willing to pay more for it, then there may be no real change to the system. Such a result would likely lead to dissatisfaction with the program and perhaps a backlash against green electricity offerings.

Company disclosure addresses the weaknesses of product disclosure by precluding segregation of clean from dirty resources within a company. This has some appeal, in that companies will have to clean up their mix in order to claim that they are clean. Company disclosure is also appealing from an informational perspective. That is, customers have an interest in and perhaps a right to know where their supplier gets all of its energy, not just the portion that the supplier wants to report.

IS PRODUCT DISCLOSURE A SHAM?

There has been some controversy about product-based disclosure. On one side, critics claim that if existing resources can be allocated to "satisfy" green demand, then a market with product disclosure will produce no new clean resources and misleads the customers who are paying more for electricity, presumably thinking that they are "making a difference." Proponents of a product approach to disclosure claim that this reallocation is merely a near-term phenomenon, and that over time the growing customer demand for clean power will lead to the addition of new cleaner resources (see, for example, Working Assets, 1997).

In large measure, this disagreement boils down to the numbers. That is, how does the supply of existing "clean" resources compare with the demand in a competitive electricity market? If the demand might exceed supply then there is some validity to the idea that product disclosure could make a difference. If the demand is likely to be less than the current supply, then product disclosure looks more like customer fraud.

Ed Holt has compiled an excellent summary the results of green pricing programs and market research (1997). It is clear from his summary that there is a very high degree of interest in green power from electricity consumers, as expressed in surveys and focus groups. There is also a significant "gap" between market research and actual customer behavior. Ed Holt concludes that "Only a well-designed

program, properly introduced and marketed, and adequately supported and sustained over a period of several years will establish how big the market truly is” and that “Unfortunately, such a program does not yet exist.” (page 14, Holt, 1997). For illustration in simple and optimistic terms, if we take the green market to be 10 percent of residential sales and 2 percent of commercial sales, the total would be about 4 percent of the electricity sold in the U.S.

The sources of energy for electric generation in the U.S. in 1995 were:

Coal	55.2 %
Oil	2.0 %
Gas	10.3 %
Nuclear	22.5 %
Hydro	9.8 %
Other	<u>0.2 %</u>
Total	100.0 %

Source: EEI, 1997.

The “other” portion of this includes generation by geothermal, wood, waste, wind and solar (EEI, 1997), and is dominated by geothermal (page 14, EIA, 1995).

With these figures in mind, if that “green demand” of 4 percent were entirely for electricity from non-hydro renewables, then it would be likely to cause some changes in the generation mix. On the other hand, if the “green demand” is less focused, and can be satisfied by hydro generation or even the cleaner fossil fuel generation such as natural gas,¹ then the prospects for changing the mix through green marketing with a product approach are dim.

THE TWO COMPONENTS OF THE GREEN MARKET: MANDATORY COMPANY DISCLOSURE AND SPECIFIC REAL PRODUCTS

Fortunately, mandatory company disclosure is not at odds with suppliers offering incremental green products. It is entirely possible to require companies to disclose basic information about their fuel mix and key air emissions and at the same time to have marketers creatively develop and offer specific green products. Indeed, these two aspects of the market complement each other well.

Mandatory disclosure can be designed to avoid burdensome requirements and can stick to simple facts. It can provide a background of information for consumers, primarily about the existing generation mix, which will change only slowly over time. It can satisfy customer needs for basic, standardized information about the electricity sources of competing suppliers.

At the same time, market participants will develop all sorts of new products and make all sorts of claims. These might involve promises about building new renewable resources and might involve value judgements about which resources are good and which are bad. These claims will have to satisfy

¹ Ninety percent of Working Assets electricity sold in New Hampshire was from hydro and natural gas, satisfying its representation to potential customers that “85% of the power would come from renewables and natural gas” (Working Assets, 1997).

standards for truth-in-advertising, and perhaps comply with specific requirements yet to be developed for electricity marketing.

With this two-part approach, large companies with existing, dirty power plants can develop green products -- but the projects will have to be incremental. Customers who buy a green product from a dirty company should know both sides of this: that the company is coal-based, and that the renewable product is incremental.

With this view of the Future, mandatory disclosure is not the primary vehicle for getting new, clean resources into the market. Rather, disclosure provides useful, standardized information to customers, setting a stage that will minimize bogus marketing claims and provide a foundation upon which serious marketers of incremental renewable power can build.

POWER POOLS AND SPOT MARKETS

Electric power pools have system agreements, approved by FERC, that lay out protocols for dispatching power plants and for billing. A typical arrangement has the actual dispatch optimized on a combined basis, that is, all of the available generators are used in a least-cost manner to serve total pool hourly loads. Then, for accounting purposes, each company is assigned its own units first toward its own load. The result will be that some companies generate more than their own load and some companies generate less. Energy transactions are then assumed in order to balance the system, and buyers compensate sellers according to the pricing provisions in the system agreement (marginal cost plus ten percent and "split-savings" are two pricing schemes). The pooling agreement and accounting systems could be modified to unambiguously allocate generation from each company's owned units either to its own load or to sales. In situations where a number of companies sell in the pool, perhaps to several buyers, the sources of generation would be known, and attributed to the buyers, perhaps on a pro rata basis. With restructuring, much of this will remain the same, but dispatch will in many cases be based on bids rather than costs.

In effect, the tracking system can work by following the dollars. For any time period, there is a known amount of electricity generated, and a known amount of electricity consumed. These should be equal, after accounting for losses. The buyers at retail compensate the generators, perhaps in some cases with several intermediaries. By following the contracts and the flow of money from retail consumers to generators one can develop a reasonable idea of accountability.

DATA AVAILABILITY ISSUES

Each company registered to sell electricity to retail customers in a state would have to provide information about its resource portfolio, including the fuel mix and rates of air emissions per kWh generated. This could be based largely upon information already measured and reported to the EPA, FERC, and EIA. The main databases of such information are:

- Form EIA-860, "Annual Electric Generator Report,"
- FERC Form No. 714, "Annual Electric Control and Planning Area Report,"
- "Wholesale Electric (Bulk Power) Trade data," compiled from Form EIA-412, Form EIA-861, Form FE-781R, FERC Form 1, REA Forms 7 and 12, and
- EPA's continuous emissions monitoring data.
- Quarterly power marketer reports to FERC.

This information provided is sufficient to implement a reasonably workable environmental disclosure system. However, there are problems with 1) timing of data availability, 2) coverage of data, and 3)

future accessibility given competitive sensitivities. Moskovitz et al (1997) discuss data availability to support disclosure.

The time lag for data availability is a particularly daunting problem for a disclosure system. Some reports, such as the FERC Form No. 1 are filed in the spring of the following year. Aggregation of these data can take even longer. For disclosure to work well, fresher information will be needed. Fortunately, most necessary information is available to system operators on an almost real-time basis.

Any system, unless implemented for an island, will have coverage issues. Even if the system were implemented consistently for the entire U.S., there would be imports from Canada and Mexico to deal with. How should purchases from outside the system be treated? A set of protocols is needed for imputing a source -- and thus fuel mix and emissions -- to transactions. For example, if it were the case that a purchase was made from a specified generating unit in a neighboring system and that system had a similar set of protocols for emissions accounting, then it may be reasonable to use the unit-specific emission rate. If, on the other hand, the purchase were not from a specific unit, or the neighboring system had no emissions accounting system, then it might be reasonable to impute emissions to the transaction based upon the selling system's marginal emissions rates, or even the worst unit on the selling system.

Power marketers will be a rapidly increasing role in electricity markets. The reporting requirements for power marketers need not include prices, but quantities of electricity bought and sold must be reported, with the other company identified. Spot markets and futures markets are sure to develop and play an important role. These do not cause any particular data problem for a disclosure system, as long as the energy quantities are tracked and reported. The tracking is a given since financial compensation to generators depends on it. Whether the data are reported to entities that can implement or verify a disclosure system is a more difficult question. The answer will depend upon what policies are put in place to require it.

The essential data for a disclosure system include generation by plant, and the buyer, seller and quantity of energy for each transaction. Procedures should be implemented that respect legitimate confidentiality concerns of market participants while ensuring that sufficient data to implement an environmental tracking system -- and to allow regulatory oversight of market power and electric system reliability. Where Independent System Operators are created, they should play a key role in implementing the tracking aspect of environmental disclosure. ISO's have the technical expertise, the necessary information on generation and transactions, procedures for handling sensitive data appropriately, and the independent status for credibility.

A SIMPLE SYSTEM: COMPANY-BASED WITH WHOLESALE SALES FIRST

There are a variety of ways to approach the treatment of transactions in an environmental disclosure system for electricity. The most straightforward, and ultimately perhaps the best, approach is described below -- a company-based wholesale sales first approach. This simple system divides electric companies into their production and retail functions. Wholesale sales are assumed to be from producer's own generation, unless the producer sells more at wholesale than it produces. If wholesale sales exceed own generation, then the extra is assumed to come proportionately from the companies the producer purchases from. This approach allows the complex web of electricity transactions to be dealt with in a straightforward manner, avoiding the difficulties and ambiguities of tracing power transactions back through several companies.

By separating the production and retail functions, this simple system shows great flexibility for representing the many types of entities and transactions that will occur in the market. Transactions from outside of the system might be treated differently than transactions within the system. For example, it may be appropriate to attribute marginal emissions and fuel mix to imports.

OTHER SYSTEMS

The approach described above is the most straightforward way to account for transactions. Other approaches that account for the web of transactions in a more subtle way are conceivable. For example, a wholesale sales first convention might be adopted. Or alternatively, each company might be seen as selling a slice of its own generation and its purchases -- to both its wholesale customers and its own retail customers. However, because the transactions comprise a complex web, and not a unidirectional chain, these approaches are more complex. They can involve working back through sometimes many companies to find the mix for a single buying company. The implementation of some of these approaches would require sophisticated mathematical tools (e.g., linear programming) to implement.

It is also possible to take the product approach, and base the treatment of transactions on what the contract says about the source. This could be implemented using the framework outlined above, but with generators that are allocated through contracts assigned accordingly. There would still be some unspecified transactions and sales from a "slice of the seller's system" for which the tracking algorithm of wholesale sales first will be a useful method.

CONCLUSION

Mandatory disclosure of fuel mix and key environmental attributes should be included in the design of competitive retail electricity markets. The system should be designed such that consumers really can make a difference to the generation mix. Tracking transactions is feasible -- but there are various possible approaches so it will be important to pick one and use it consistently.

It should be noted that specific policies could be implemented without a comprehensive system of attribution. For example, a renewable portfolio standard (RPS) with tradable credits is an easy system to implement, because it is not necessary to attribute generation to sales. An RPS requires only that: 1) particular renewable projects be certified and given renewable energy credits (RECs) based upon output, and 2) part of the certification process for retail sellers of electricity be a requirement that each holds the necessary number of RECs to cover its total retail sales multiplied by the overall renewable target fraction. An air emissions trading system that is applied at the plant stack is a similar approach.

The disclosure systems that are the subject of this paper are, in effect, implemented at the customer's meter rather than the plant stack or the busbar. It will, in some circumstances be important to coordinate the two types of systems so that they can work well together. For example, a well-designed environmental disclosure system should not undermine a renewables portfolio standard.

Also, it is important to bear in mind that electricity generation has large negative consequences for human health and the environment that are not internalized through regulations. Environmental disclosure and green marketing rely upon the willingness-to-pay of consumers acting individually. This is not a substitute for people acting as citizens to put in place real energy and environmental policies. These can include market-based mechanisms such as pollution taxes and cap and trade systems, which serve to internalize some of the environmental impacts that are currently external to energy markets.

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A FULLY UNSTEADY PRESCRIBED WAKE MODEL FOR HAWT PERFORMANCE PREDICTION IN YAWED FLOW

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ABSTRACT

This paper describes the development of a fast, accurate, aerodynamic prediction scheme for yawed flow on horizontal axis wind turbines (HAWTs). The method is a fully unsteady three-dimensional model which has been developed over several years and is still being enhanced in a number of key areas. The paper illustrates the current ability of the method by comparison with field data from the NREL combined experiment and also describes the developmental work in progress. In particular, an experimental test programme designed to yield quantitative wake convection information is summarised together with modifications to the numerical model which are necessary for meaningful comparison with the experiments. Finally, current and future work on aspects such as tower-shadow and improved unsteady aerodynamic modelling are discussed.

INTRODUCTION

Historically, design assessments of the aerodynamic performance of horizontal axis wind turbines have been satisfactorily conducted by relatively simple blade-element momentum methods^{1,2}. Such methods are both adequate and fast for the purpose of gross performance assessment but, when time-dependent details of the local flow states are required, other methods must be employed. This is particularly the case if aeroelastic tailoring of the blades is to be achieved. Currently, detailed aerodynamics can be provided by vortex wake methods and they represent the most sophisticated tools available for aerodynamic design. The purest application of the vortex method is the so-called free wake method^{3,4} in which the turbine is represented by filaments of trailing and, depending on operating conditions, shed vorticity which are free to convect at will. The associated computation times associated with such methods are, unfortunately, very high. This mitigates against their use in day to day design and prohibits coupling with an aeroelastic analysis scheme. As a result, more efficient schemes are being actively developed.

Prescribed wake modelling has, for many years, been seen as a viable alternative to more intensive free wake methods in providing aerodynamic performance estimates for helicopter rotors. This approach was successfully applied by Basuno et al.⁵ to vertical axis wind turbines and later extended by Coton et al.⁶ to address unsteady aerodynamic effects on these machines. The fundamental difference between a prescribed wake method and free wake models lies in the manner in which the wake geometry is obtained. In free vortex models the wake shape is created by consideration of self-induced velocities and can either be built up gradually over a number of time steps or obtained by a large number of successive gross distortions of the entire wake geometry. Both of these techniques can be very time consuming and, although some innovative calculation strategies have evolved, the scope for substantial run-time reductions is limited. In the present study, a prescribed wake model, which uses simple geometry prescription functions derived from consideration of momentum theory, has been developed for horizontal axis wind turbine applications. In this model the wake geometry is generated without regard to the wake self-induced velocities calculated by free vortex type models. Rather, the fully developed wake shape is obtained purely by consideration of induced velocities at the turbine blades. In this way the wake geometry can be viewed as an input to the problem rather than part of the solution and so computation times are substantially reduced.

It should be emphasised that, in the present scheme, the wake shape is uniquely related to the induced velocity at the blades through the input wake prescription functions. It is, therefore, essential that these functions adequately represent the physical processes inherent in the wake evolution in such a way that they are universally applicable regardless of the blade loading distribution. Development of these prescription functions has been hampered by a lack of reliable empirical information. In fact, of the experiments which have examined wake convection, few if any have provided simultaneous blade loadings. In this study, much computational and experimental effort has, therefore, been directed towards validation of the functions used in the model.

In the following sections the operating principles of the prescribed wake model are described together with the numerical techniques used to establish the prescription functions. In addition, a new experiment in which wake convection is measured simultaneously with blade surface pressures is described. Consideration is also given to the manner in which aerodynamic scaling considerations and the test environment is accounted for in the numerical model. Finally, areas of future model development are outlined.

THE PRESCRIBED WAKE MODEL

Precise details of the computational implementation of the prescribed wake model can be gleaned from Robison et al.^{7,8} but the main features are summarised here.

In order to provide a detailed assessment of the variation of aerodynamic coefficients across the blade span, each blade is divided into a number of spanwise elements which are considered to be aerodynamically independent. The blade division is carried out in a manner which yields a finer distribution of elements at the blade tip, so giving a more accurate representation of the rapidly changing aerodynamic conditions associated with this region. The distributed loading along the blade is approximated by assuming a uniform loading on each blade element which is evaluated at the quarter chord of the element mid-span. The spanwise blade loading distribution is then represented by a series of straight-line vortex filaments which lie along the quarter chord line of each blade element, the strengths of which are evaluated by application of the Kutta-Joukowski theorem on the basis of 2-D aerofoil data.

By representing the turbine blades in this manner, a discontinuity in spanwise bound circulation is created at each element boundary. This is redressed by the introduction of trailed vortex filaments whose strengths correspond to the differences in bound circulation between adjacent blade elements. Similarly, the changes in blade incidence associated with yawed flow require the introduction of shed vorticity into the wake to account for temporal changes in bound circulation. By discretising the rotation of the blades into a series of time steps, the wake is generated as a helical mesh of straight line shed and trailed vortex filaments which extends downstream from the blade trailing edge. On a multi-bladed system, each blade generates its own wake structure which is superposed on those from the other blades.

The flow passing through the swept area of a wind turbine experiences a deceleration in the streamwise direction and, from continuity, a corresponding expansion in the cross-stream direction. The axial deceleration of the flow is not an instantaneous phenomenon but begins ahead of the turbine and continues until the flow reaches a new equilibrium condition in the far field. Consequently, the wake may be thought of as consisting of two distinct regions; the near wake in which large scale changes in wake geometry occur and the far wake which represents the far field equilibrium condition of the flow. In the present scheme, the near wake geometry is defined by simple prescription functions which map the wake induced velocities from the turbine blades to the far field equilibrium condition. The physical extent of the near wake is dictated by a cut-off criterion which is expressed as a universal non-dimensional time constant. This strategy allows the extent of the near wake to vary with operating conditions, yielding a more flexible criterion than linking the cut-off to a length scale.

Simple momentum theory dictates that the axial induced velocity in the far field is twice that at the turbine blades. When considered in more detail, however, it would be unreasonable to expect this relationship to hold for the variation in streamwise velocity of a particular vortex filament. Indeed, in the tip region, where large spanwise gradients in flow conditions exist, significant departures from the basic momentum relationship could be expected. For this reason, the far field induced velocity is defined in terms of the on-blade conditions using a deficiency function whose value varies along the span. Once the

near-wake cut-off criterion has been satisfied, flow conditions in the far wake are assumed to be constant resulting in a cylindrical, axisymmetric flow field.

The complex nature of the flow field means that the parameters which define the wake development are, to a great extent, inter-dependent. Thus, determination of appropriate prescription parameters is problematic if detailed information on the wake structure for a variety of different tip-speed ratios is not available. This was found to be a problem in the present study as comprehensive and reliable test data were not available to assist in the code development. This could have been overcome by the use of a free-wake model to provide the required information but the run times incurred by such schemes limited this approach. A novel and more acceptable technique was, therefore, developed during this study. This involved the use of a hybrid prescribed/free wake scheme to determine the optimum solution for the induced velocity functions, near wake cut-off criterion and far wake deficiency function. In this technique, an imaginary high resolution grid, defining a series of node points, was positioned behind the turbine. This technique, which is illustrated for simplicity in a two-dimensional manner in Fig. 1., allowed the induced velocity components to be calculated at each node point and subsequently compared to those prescribed. By starting from an initial approximation to the required prescription functions, the information from these node points could be used in an iterative loop to provide feedback on the suitability of the current wake shape. This iterative process was continued until the feedback from the grid nodes matched the prescribed velocity distribution throughout the wake over a wide range of tip speed ratios.

It was found that the most appropriate geometry was obtained when the radial induced velocity variation in the near wake is expressed as a quadratic function of time. The corresponding axial induced velocity is defined as three sub-regions in each of which the velocity development is a linear function of time. These relationships are applied over the entire near wake region which is assumed to reach the far wake state after a fixed non-dimensional time has elapsed. The corresponding spanwise variation of the far wake deficiency function is described in Ref. 7. As in previous studies on prescribed wake modelling of vertical axis wind turbines⁹, the wake prescription functions have been found to be relatively insensitive to realistic changes in blade planform, solidity and, consequently, the number of blades. The numerical implementation of the model is similar to that of Basuno et al.⁵ although, in this case, a first order Newton scheme is used to provide a converged solution for the blade loadings for a given wake geometry. The overall calculation procedure is outlined in Fig. 2.

Studies of yawed wake structures using the hybrid free/prescribed wake method were also conducted for a range of operating conditions including yaw angles up to 60 degrees. It was found that the principle effect on the wake structure occurred through the loading imbalance on the disc. It was found that when the induced velocity variation resulting from this imbalance was fed into the existing wake prescription functions, an adequate representation of the yawed wake was obtained. Thus, the prescription functions developed for head-on flow were found to be universally applicable to yawed flows. A typical wake structure calculated by the model in yawed flow is presented in Fig. 3.

Another consequence of yawed inflow can be the introduction of unsteady aerodynamic loads on the blades. Unsteady effects are manifest if the reduced frequency of the effective pitching of the turbine blade is high enough. The loads produced under these circumstances can be much higher than the equivalent steady-state loads and may have important life-cycle implications for a wind turbine. This phenomenon has received much interest in the past few years and is clear that a comprehensive aerodynamic prediction scheme must be capable of modelling such effects.

In the present scheme, unsteady loadings are modelled by coupling the unsteady aerodynamic model of Leishman and Beddoes¹⁰ to the prescribed wake method. The main features of this technique may be summarised as follows: (1) Unsteady effects during attached flow conditions are simulated by the superposition of indicial aerodynamic responses. (2) Nonlinearities in aerofoil behaviour, related to small amounts of trailing edge separation, are represented using a Kirchhoff flow model. The movement of the unsteady flow separation point position is related to the static separation position via a deficiency function. (3) The onset of leading-edge separation (and hence, dynamic stall) is identified using a criterion based on the attainment of a critical local leading-edge pressure which is further related to the normal force. For unsteady conditions, a lag in the normal force response to changes in angle of attack and a lag in the leading edge pressure response with respect to normal force have to be taken into

consideration. (4) The induced vortex force and the associated pitching moment are represented empirically in a time dependent manner during dynamic stall.

The unsteady aerodynamic model requires information such as the reduced pitching rates, the local relative velocity and the instantaneous angle of attack which the turbine blade experiences. In the unsteady prescribed wake method this information is determined by initial application of the prescribed wake scheme using static aerodynamic characteristics. This stage of the calculation procedure also produces the wake geometry for the subsequent dynamic calculation. On completion of this stage, the unsteady aerodynamic model is used iteratively with the wake model to obtain a more accurate estimate of the turbine performance. As the stability of the indicial approach can be sensitive to the calculation time step, a final series of iterations are conducted with an increased number of azimuthal steps.

In modelling the performance of an aerofoil in unsteady flow, the technique described above implicitly includes the induced effect of the shed wake structure downstream of the aerofoil. Similarly, the wake structure generated in the prescribed wake method contains filaments of shed vorticity and their induced effect on the blade flow field is calculated directly by application of the Biot-Savart relationship. Consequently, coupling of the two schemes is hindered by this duplicative effect. As shown by Coton et al.⁶, this can be overcome by selectively neglecting the shed wake terms from the prescribed wake model and calculating the induced effect via the unsteady aerofoil performance scheme. In this case, only the influence of the wake element on the blade element from which it is shed is removed from the prescribed wake model. Thus, in a two bladed system, the induced effect which the wake from blade one has on blade two, and vice-versa, is calculated directly by the prescribed wake method. The effect on a blade of the vorticity trailed from that blade and of shed elements produced by other sections of the blade are also calculated by the prescribed wake model.

TYPICAL CALCULATIONS

Model validation for head on flow conditions was carried out and is discussed in detail by Robison et al.⁸. As an example of this, Fig. 4 shows predictions of generated power for the MOD-1 turbine compared with field measurements and numerical predictions obtained from the free wake method of Afjeh and Keith³. The predicted values from the prescribed wake method compare well with these results over the entire range of operating conditions. The largest differences between the free and prescribed wake predictions can be seen to occur at low wind velocities, where the wake structure is highly concentrated. This introduces the possibility of blade-vortex and vortex-vortex interactions which may compromise a solution. It is pertinent to note, however, that a free vortex method will be more sensitive to these effects than a prescribed wake scheme. Nevertheless, both calculations are within the scatter of the field data.

Whilst overall performance is a useful indicator of gross predictive capability, it is more informative to examine load variations at various locations along the blade span. In Fig. 5, the predictions of blade normal force coefficient from the model are compared with field data from the NREL combined experiment¹¹ in head-on flow conditions at two blade span locations. In both cases, the model compares well with the experiment except in the region of tower shadow.

The capability of the model to calculate blade loadings associated with yawed flow is illustrated in Fig. 6 where the predicted normal force coefficient variations at four blade span locations are compared with data from the NREL combined experiment at a yaw angle of thirty degrees. At 80% of span, the general level of agreement between prediction and experiment is excellent. Moving inboard, however, the quality of prediction deteriorates, particularly over the first part of the cycle. Once again, the tower shadow effect on this downwind turbine is clearly visible in the experimental data around 90 degrees azimuth but is not present in the calculation.

EXPERIMENTAL STUDIES

In an attempt to provide empirical validation of the prescription functions developed above, an experimental test programme was initiated. In this programme, the intention was to obtain simultaneous blade surface pressures and wake convection information in the controlled environment of a wind tunnel. This type of scale model testing is fraught with difficulty since normally only partial similarity with larger scale turbines is possible. The effect of the wind tunnel walls is also an added complication since they,

inevitably, apply an unrealistic constraint on the wake expansion. For this reason, the testing strategy had two subsidiary elements which were designed to address the difficulties described above.

In a scale model test, it is relatively straightforward to match the tip speed ratio of larger machines. This, however, often introduces difficulties since the resulting blade chord Reynolds number on the test turbine will be considerably lower than that on the larger turbine at the same tip speed ratio. For modelling purposes, this is not a significant problem since a prediction can be made on the basis of either case provided the blade section characteristics at the particular Reynolds number are known. For this reason, a series of low Reynolds number tests were conducted on the aerofoil profile to be used for the turbine blade section. The particular section chosen for the test turbine was the NACA 4415 aerofoil. Although several datasets were already available for this aerofoil, they either did not cover the required Reynolds number range or were conducted in poor conditions¹².

Low Reynolds number tests, covering the chord Reynolds number range 100000 to 600000, were conducted in the 1.15m x 0.83m low speed wind tunnel of the University of Glasgow. The tunnel-spanning model had a chord length of 0.3m and consisted of a glass fibre skin filled with epoxy foam. The model had sixty surface pressure tappings distributed across the mid span which allowed the nominally two-dimensional surface pressure distribution to be obtained. Drag estimates were made using a ZOC electronic scanning module connected to a pitot rake mounted aft of the model on a two-dimensional traverse. By moving the pitot rake in small increments, it was possible to obtain high spatial resolution for these measurements. The traverse was controlled by a Macintosh Microcomputer via National Instruments LabView software. A schematic of the general experimental set up is shown in Fig. 7.

The results obtained in this part of the study provided the necessary blade sectional data input to the prescribed wake model to allow comparison with the model turbine tests to be made. Unfortunately this was not sufficient to ensure a valid comparison since the effect of the wind tunnel walls had also to be considered. To do this, it was necessary to couple the prescribed wake model with a numerical representation of the tunnel walls. The particular method used to model the solid boundaries was the three-dimensional source panel method of Hess and Smith. This had been used in a previous study at Glasgow to determine the convection of the wake from an isolated horizontal rotor by combining it with a free wake calculation¹³. At present, work on coupling the prescribed wake model to the panel method is at an advanced stage.

The final stage of the experimental programme is the main test series on the model turbine. The objective of this part of the project, which is being conducted in collaboration with a team from the Fluid Loading and Instrumentation Centre of Heriot-Watt University, is to simultaneously measure the wake convection characteristics and blade surface pressures on an outboard section of the turbine blades in both head-on and yawed flow conditions. Such a measurement programme is significantly enhanced by the unique capabilities of the two Universities involved.

A fully automated data acquisition system for the measurement unsteady pressures at high spatial and temporal resolution has been developed at Glasgow University. This system has two-hundred channels, each of which is capable of sampling to a maximum rate of 50KHz, giving an overall sampling rate of 10MHz¹⁴. In addition, the group at Glasgow has considerable experience in measuring unsteady pressures on rotating blade systems. The Heriot-Watt group are specialists in Particle Image Velocimetry (PIV) and have successfully applied the technology to flow measurements on small and full-scale wind turbines^{15,16}.

The test programme is due to commence in June 1997 and will take place in the University of Glasgow 2.13 x 1.61m low speed wind tunnel. The turbine model, which is a two-bladed upwind design and has a rotor diameter of 1m, has been specifically designed to maximise the available internal space for instrumentation. The blades have been manufactured from carbon fibre and have a chord length of 0.1m and will accommodate miniature pressure transducers. The internal structure of the nacelle has been constructed from aluminium and houses the rotating shaft of the turbine. On this shaft are located the necessary electronics to condition the signals from the pressure transducers prior to passing the signals through slip-rings located at the rear of the nacelle. The speed of rotation is controlled by an electronic

braking system/drive motor located below the wind tunnel floor and connected to the turbine shaft by a belt and pulley system. A schematic of this arrangement is illustrated in Fig. 8.

The experimental set-up which will be used in the wind tunnel test programme has already been extensively tested in a smaller wind tunnel at Heriot-Watt University and is described in detail in Ref. 15. During testing, the wind tunnel will be operated in saturation seeding mode and so give consistent and effective images that can be obtained quickly and reliably without the need to introduce run time seeding. The illuminating laser, recording camera and pressure measurement system will be synchronised to a preselected triggering, appropriate to a particular phase of the turbine cycle. Tests will be conducted over a range of yaw angles and tip-speed ratios. Additional tests will also be conducted in yawing flow to study the wake dynamics.

CONCLUDING REMARKS

The information presented in this paper represents the current status of the prescribed wake aerodynamic model being developed at Glasgow University. At present, the model is capable of predicting both steady head-on flow and yawed flow performance. Experiments are currently under way to provide further validation of the wake prescription functions used in the model. There are still, clearly, areas of improvement within the modelling strategy, particularly in relation to highly yawed flows. In the near future, three particular modelling problems will be targeted.

Firstly, the present model lacks a tower shadow representation. Preparatory work on this aspect is already under way. Secondly, the unsteady aerofoil performance prediction scheme is not ideally suited to very high angles of attack in its present form. This presents a problem when considering highly yawed flow where angles of attack on the first half of the cycle may be very high. This is illustrated in Fig. 9 which presents the blade angle of attack variations corresponding to the normal forces presented in Fig. 6. It is clear that the main areas of disagreement in the normal force traces correspond to very high angles of attack. The unsteady model also requires some specific modifications to become directly applicable to low speed flows on the type of aerofoils used on wind turbines. This is a consequence of the history of the model in its use for high speed flows on helicopter rotors.

Finally, the influence of three-dimensional effects on the inboard sections of wind turbine blades has received considerable attention in recent years. In fact, even if the unsteady aerodynamic model were correctly adjusted for the angle of attack range experienced by the blades, a poor level of agreement would still be expected at 30% of span because of the three-dimensionality there. As noted by Pierce and Hansen¹⁷, it is possible to overcome this problem by modification of the input aerofoil data. Nevertheless, it is hoped to develop a modelling strategy to provide a robust solution to this problem in the future.

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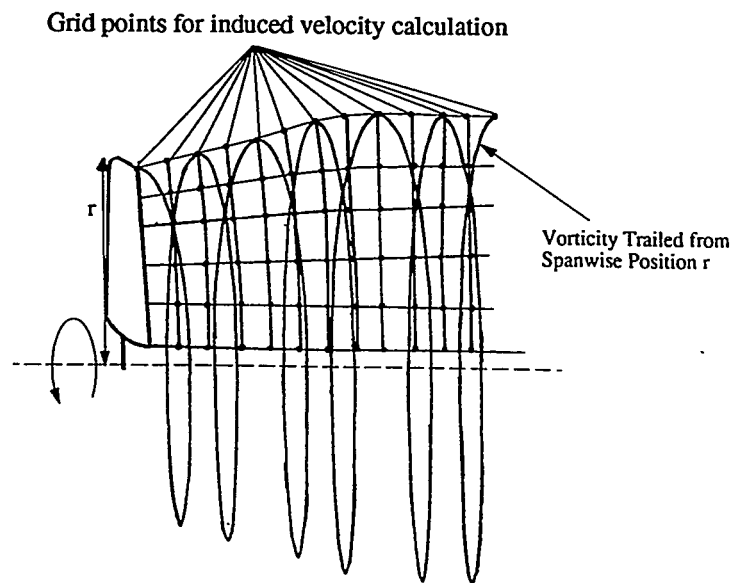


Fig. 1. Idealised representation of imaginary grid behind turbine blade in two-dimensions. Only the trailed wake from the tip element is shown for clarity.

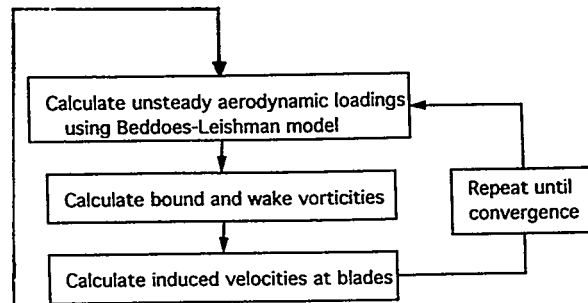
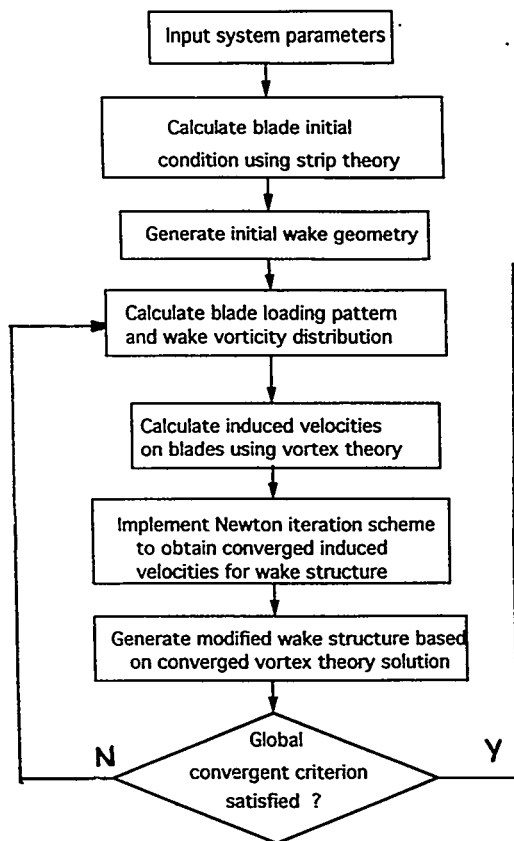


Fig. 2. Outline of the prescribed wake calculation procedure

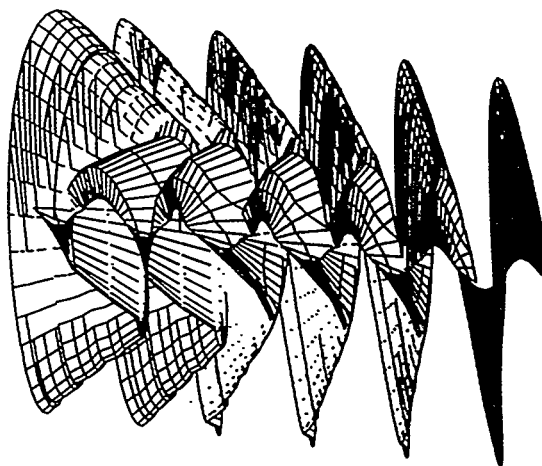


Fig. 3. Typical wake structure in yawed flow

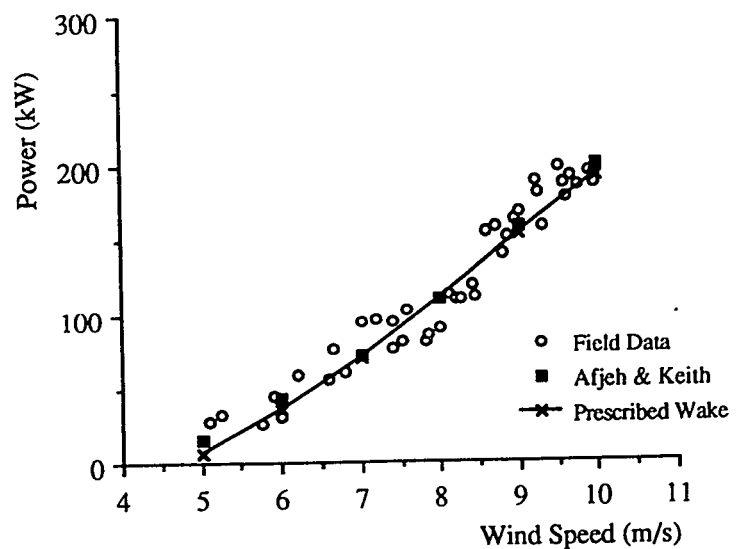


Fig. 4. Predicted and measured power curve for MOD-1 wind turbine

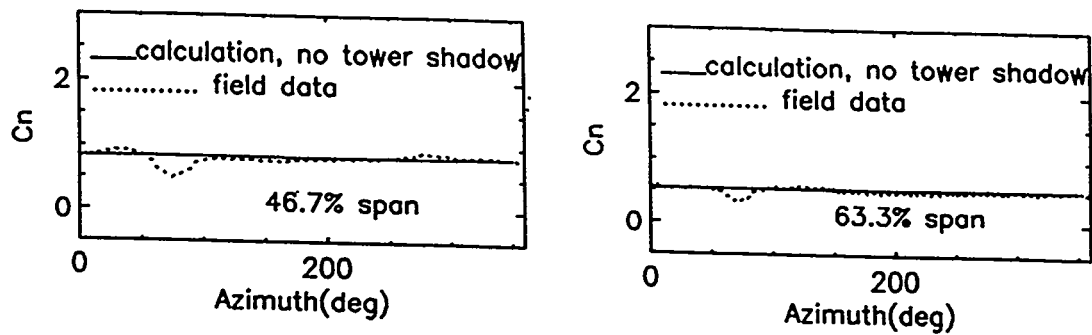


Fig. 5. Predicted and measured normal force coefficients at two blade span locations on the NREL combined experiment turbine in head-on conditions

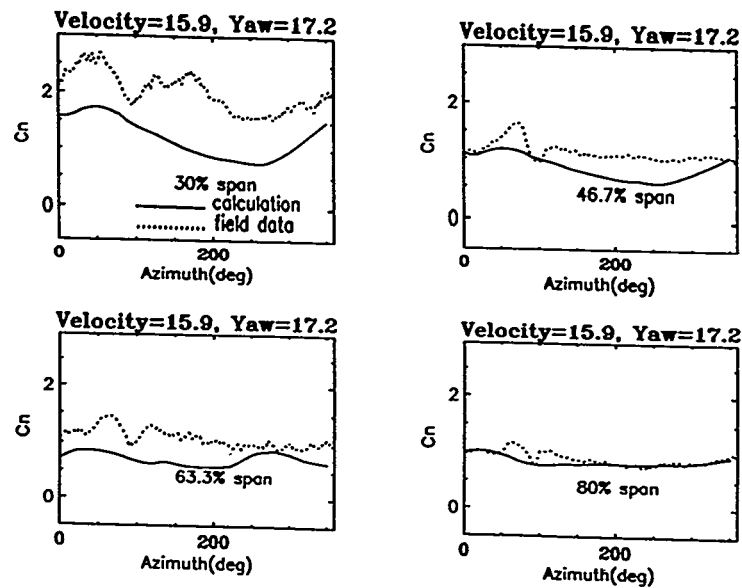


Fig. 6. Predicted and measured normal force coefficients at four blade span locations on the NREL combined experiment turbine at a yaw angle of 30 degrees

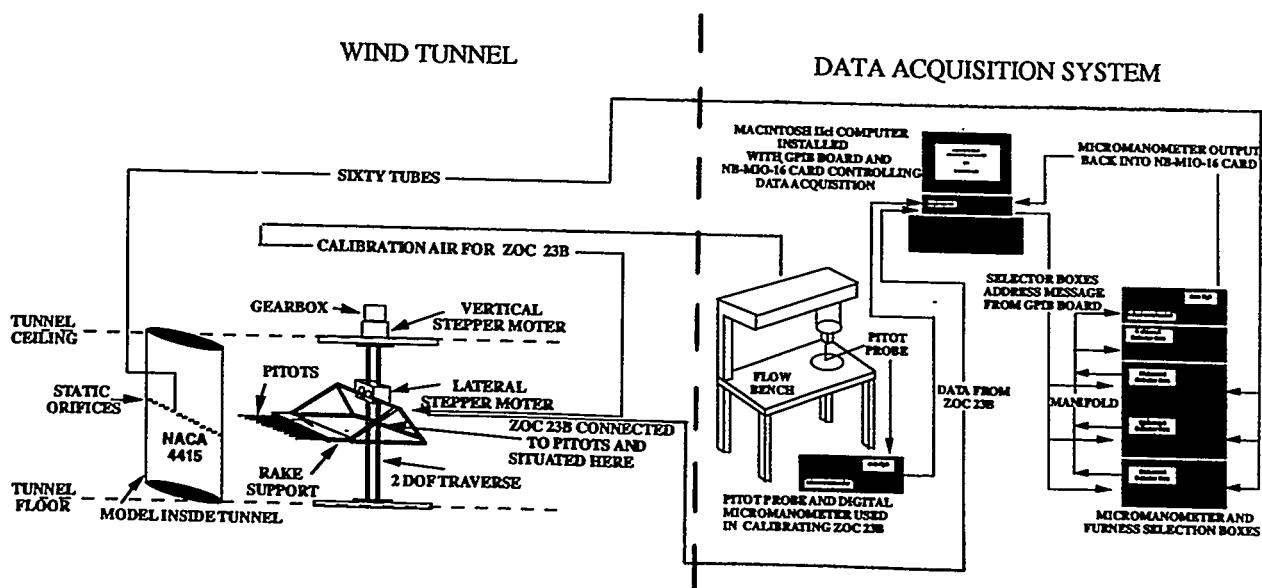


Fig. 7. Schematic of the low Reynolds number aerofoil test set-up

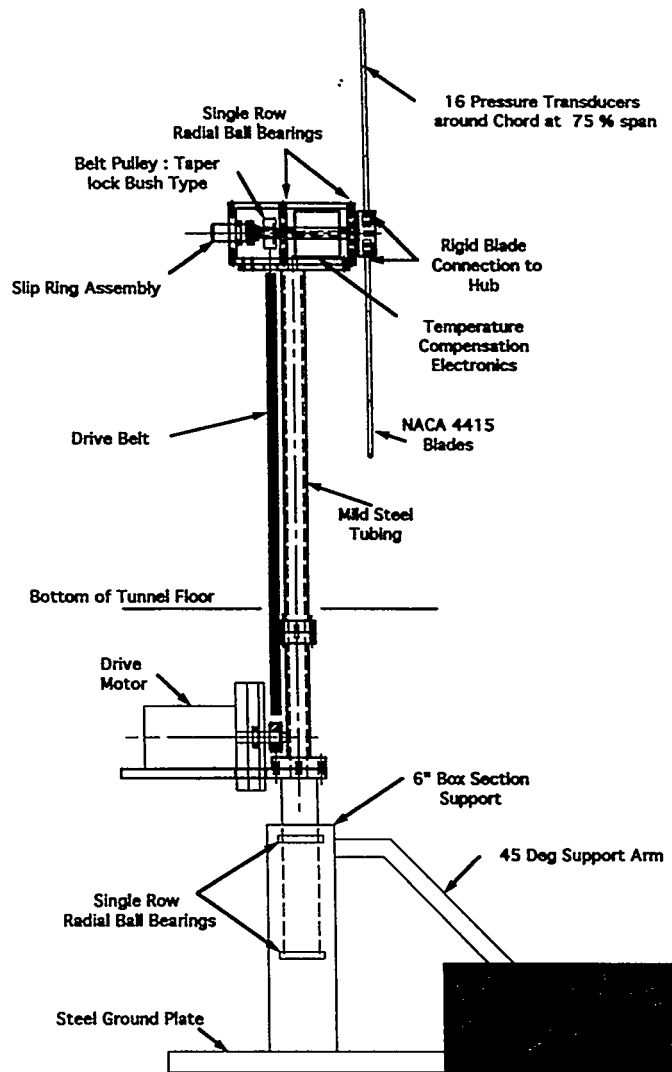


Fig. 8. Diagram of the wind turbine model constructed for unsteady pressure and PIV tests

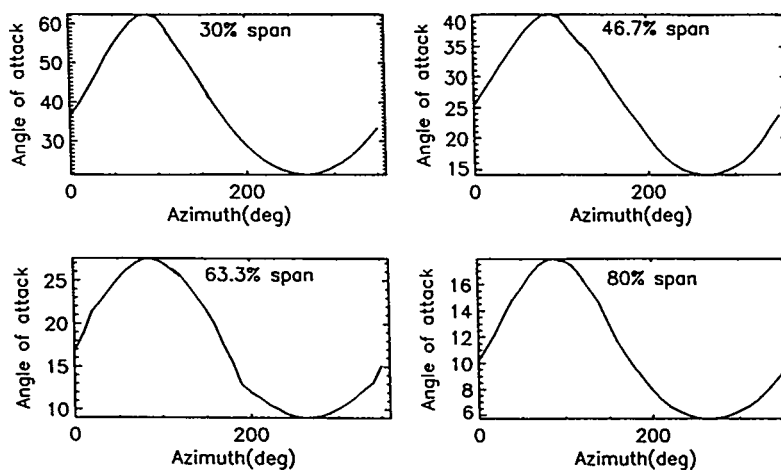


Fig. 9. Predicted incidence variation at four blade span locations on the NREL combined experiment turbine at a yaw angle of 30 degrees

EFFECTS OF LAMINAR SEPARATION BUBBLES AND TURBULENT SEPARATION ON AIRFOIL STALL

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Abstract

An existing two-dimensional, interactive, stall prediction program is extended by improving its laminar separation bubble model. The program now accounts correctly for the effects of the bubble on airfoil performance characteristics when it forms at the mid-chord and on the leading edge. Furthermore, the model can now predict bubble bursting on very sharp leading edges at high angles of attack. The details of the model are discussed in depth. Comparisons of the predicted stall and post-stall pressure distributions show excellent agreement with experimental measurements for several different airfoils at different Reynolds numbers.

Introduction

Aerodynamic stall is used as a method of peak-power regulation by approximately half of the medium to large-size, horizontal-axis wind turbines manufactured today worldwide, with pitch regulation as the most common alternative. The trade-off between these two methods depends on how much one is willing to spend for the extra mechanical complexity, higher initial investment cost, and slightly higher O&M costs of pitch regulation for a slightly better performance. With presently available turbines, the choice depends on the many factors affecting their development and marketing. Regarding the development of future turbines over the next decades, the main factor will probably become the wind regime where the turbines are intended to operate. Looking at the annual energy production rather than at the installed cost per kW as the deciding figure-of-merit in this trade-off, a larger-rotor, variable-pitch machine will likely be the best choice in temperate climates characterized by low annual average wind speeds and Rayleigh-type wind speed distributions. A stall-regulated machine, on the other hand, is most likely to be the best choice for the narrow wind speed distributions with high average speeds characteristic of many tropical climates. Whatever one's opinion on this matter may be, stall-regulated blades will most likely remain central to wind-turbine development and operation. Furthermore, it is helpful to control the high-lift behavior also of variable-pitch blades, for smooth operation in gusty conditions. For these reasons, a reliable stall prediction program will remain a very valuable tool in the design of wind turbine blades for many years to come.

Starting with the interactive boundary-layer method of Ref. 1, we have developed a computer program, Tbvor, to aid in the design of stall-regulated blades for horizontal-axis wind turbines. Our method relies on a careful modelling of the two main processes controlling airfoil stall: the laminar separation bubble on the leading edge and turbulent separation from the trailing edge. For better clarity, it is helpful to divide the stalled behavior of a blade in two broad classifications: 1) "stall" refers to the range of angles of attack between the appearance of 10% c , where c stands for the airfoil chord, of turbulent separated flow on the upper (downwind) surface, at the trailing edge, and the maximum lift coefficient, $c_{l,max}$; while 2) "post-stall" refers to the angles of attack beyond $c_{l,max}$.

On laminar flow airfoils, the appearance of a sizable extent of turbulent separation ($> 10\% c$) usually corresponds to the top of the laminar "bucket". This condition is where the drag of the airfoil increases

more or less suddenly because the laminar bubble (or simply the transition point, at higher Reynolds numbers) moves upstream more or less quickly with increasing angle of attack, from the mid-chord toward the leading edge. As the extent of this separated flow grows from 10% c to approximately half of the airfoil chord, the lift curve of the airfoil deviates from the linear behavior and reaches $c_{l,max}$. In this regime the laminar separation bubble on the leading edge tends to be quite small and to have a small effect on airfoil performance. Furthermore, the flow over a rotating blade remains largely 2-D and the results of the present method can be used directly in blade design.

As the turbulent separation point moves further upstream of 50% c , the thickness of the separated region increases and this mass of nearly stagnant flow (relative to the blade) starts being affected by Coriolis forces and spanwise centrifugal forces in significant ways. Here is where 3-D effects start playing an increasingly important role, *delaying* further development of flow separation. At the same time, on some airfoils the laminar separation bubble on the leading edge may fail to reattach, causing a long or burst bubble to form downstream of the leading edge. Our airfoil performance predictions in this regime, although they match the wind-tunnel tests, may not be faithfully reproducing the flow over a rotating blade and should in general be regarded as slightly underpredicting the 3-D lift. Our efforts so far have concentrated on understanding 2-D stall and the idealized 2-D post-stall condition. The next step will be to generalize the present method to 3-D post-stall prediction capability.

Description of Main Physical Phenomena

This paper focuses on the formulation of a laminar separation bubble model that merges the model of Ref. 2 with the viscous/inviscid interaction program described in Refs. 3, 4. Fig. 1 shows a schematic of the bubble flowfield inside the boundary layer, whose thickness or outer limit is shown as a dashed line (“ δ ”). The bubble forms on airfoils at low Reynolds numbers because the laminar boundary layer encounters separation (“S”) before having a chance to undergo transition to a turbulent boundary layer. The separated laminar shear layer detaches itself from the surface and, due to its greater instability, reaches transition (“T”) relatively quickly. The ensuing turbulent shear layer, then, by entraining the outer flow momentum is able to “trade it in” for pressure and recover the inviscid pressure level necessary to reattach to the surface (“R”), thereby forming a pocket of recirculating fluid dubbed laminar (or transitional) separation bubble. Our daring implication is that, in a local sense, conservation of mechanical energy applies also inside the boundary layer. The shaded areas within the velocity profiles illustrate pictorially the zero net-flow condition used to obtain the height of the dividing streamline, y_D , which is useful conceptually although it is not used directly in this model.

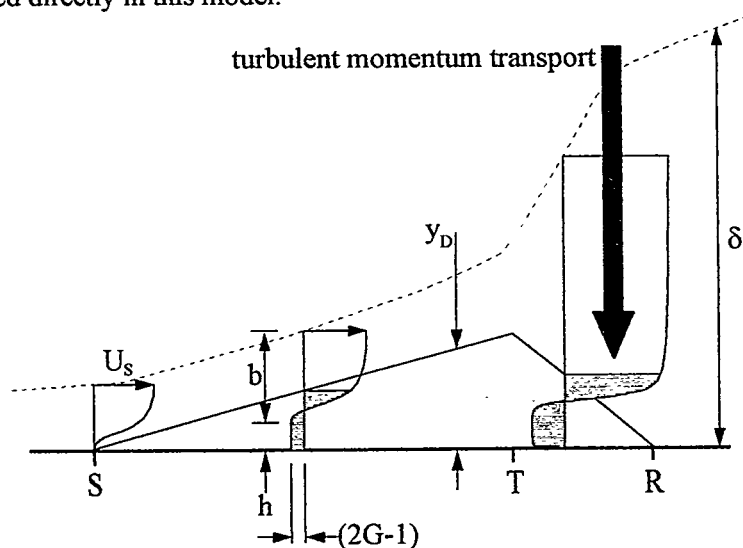


Fig.1. Schematic of the laminar separation bubble with relevant variables shown.

In the context of a stall prediction method for stall-regulated blades, the bubble is most often encountered on the leading edge, immediately downstream of the minimum pressure peak that airfoils develop at high angles of attack. In this condition it is usually very short, on the order of 1-3% of the airfoil chord. Depending on the geometry of the leading edge and on the value of the Reynolds number, the bubble 1) may have a small effect on the pressure distribution, the lift, and the drag; 2) it may cause a significant dissipation and thickening of the boundary layer resulting in losses of lift of approximately 5-10%; or 3) it may fail to reattach as a short bubble. In this last case, it is termed burst or simply a long bubble, since reattachment usually still occurs 10% c to 50% c downstream of laminar separation. The long bubble is an intensely interactive and highly dissipative flowfield which results in a drop of lift on the order of one half of $c_{l,max}$ and in a large increase in drag and moment coefficient. The bursting condition is determined by an outer inviscid pressure gradient steeper than what the turbulent diffusion process can "climb."

The turbulent flow separating from the upper (downwind) surface of an airfoil near the trailing edge, at high angles of attack, remains near the surface of the airfoil and contributes to a thicker wake than is present in attached flow conditions. This separated flow harbors a net vorticity akin to the starting vortex, where both are a direct consequence of conservation of the angular momentum of the flow. Unlike the case of attached flow at low angles of attack, however, this vorticity is not swept downstream but hovers over the trailing edge, directly affecting the circulation of the airfoil. We model this distributed vorticity with an inviscid point vortex whose strength and location we were able to correlate successfully to flow parameters such as the extent of turbulent separation and the pressure level at separation.^{3,4} The vortex rotates in the counterclockwise direction, on the upper surface, and is shown schematically in Fig. 2, together with the laminar separation bubbles.

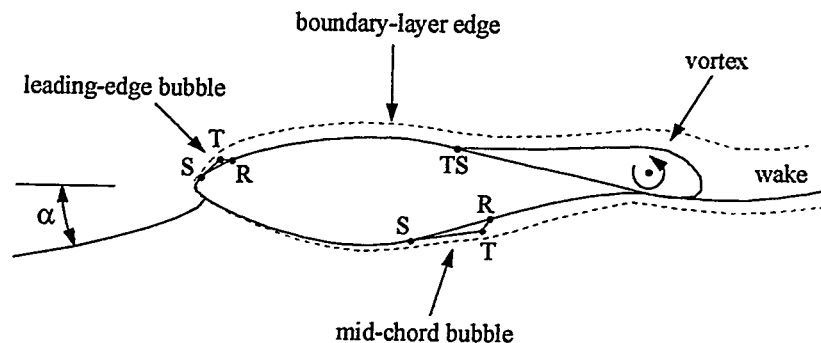


Fig. 2. Schematic of S809 airfoil in stall showing the vortex and the laminar separation bubbles.

Theoretical Model

The most important assumption of the present method is that also the flow over an airfoil in post-stall condition can be modelled accurately and reliably by an interactive boundary-layer method, complemented only by our inviscid point vortex over the trailing edge. In other words, our results seem to indicate that the basic boundary-layer assumptions of negligible pressure gradients normal to the airfoil surface and small second streamwise derivative of the velocity still hold even within the massively separated flow over an airfoil in post-stall. Apparently, the only low-order effect not modelled by a standard boundary-layer method is the vorticity of the separated flow, and this is well accounted for by the inviscid vortex. Thus, to determine the physical solution for given conditions our method relies on matching the inviscid and boundary-layer flows through a standard interactive algorithm.

Inviscid Flow

The inviscid flow is calculated by means of a panel method that uses flat panels, linear vorticity distributions along the panels, and a constant source distribution for all the panels. The Kutta condition is

satisfied by enforcing zero vorticity on the first and last panels, at the trailing edge point. As discussed in Ref. 3, this panel method has proved the most accurate for highly aft-loaded airfoils and has allowed us to forgo the use of Tavor's wake models, for the time being. The inviscid method allows the specification of a transpiration velocity, which serves to model the effect of the boundary layer on the outer flow.

The main new calculation feature related to the inviscid flow is the automatic addition and redistribution of the points defining the panels, in order to improve the resolution of the bubble flowfield. Because of the large gradients present in the bubble region, the program could not converge without adaptive variable panelling. After approximately 40 iterations the points are automatically redistributed based on the current bubble separation and reattachment locations as calculated by the boundary-layer method and the calculations are started over and brought to convergence.

Laminar Part of Boundary Layer and Separation Bubble

The laminar boundary layer is solved in the direct mode by specifying the inviscid velocity as a function of arc length, $U_i(s)$, in the two governing ordinary differential equations for the momentum and energy thickness:

$$\begin{aligned}\frac{d\delta_2}{ds} &= \frac{c_f}{2} - (H_{12} + 2) \frac{\delta_2}{U_i} \frac{dU_i}{ds} \\ \frac{d\delta_3}{ds} &= C_D - 3 \frac{\delta_3}{U_i} \frac{dU_i}{ds}\end{aligned}\tag{1}$$

where δ_2 is the momentum thickness, δ_3 is the energy thickness, c_f is the skin-friction coefficient, C_D is the dissipation coefficient, and the shape factor $H_{12} = \delta_1 / \delta_2$ is the ratio of displacement to momentum thickness. These two equations are complemented by closure correlations for c_f , C_D , and H_{12} , all expressed as functions of the shape factor $H_{32} = \delta_3 / \delta_2$. As detailed in Ref. 5, these correlations are derived in part using the Falkner-Skan family of velocity profiles. The reason the attached laminar boundary-layer closure relations are obtainable in a fairly straightforward way is that the Falkner-Skan attached profiles depend only on one parameater, which can be eliminated from the expressions for these three variables.

When laminar separation is detected, at a value of $H_{32} = 1.515095$, it is necessary to resort to an inverse boundary-layer method. The calculations are started two points upstream of separation by specifying an initial guess at the distribution of displacement thickness in the equations,

$$\begin{aligned}\frac{dH_{32}}{ds} &= \frac{dH_{32}}{dH_{12}} \left[\frac{2C_D - \frac{c_f}{2} H_{32} \left(1 + \frac{1-H_{12}}{2+H_{12}} \right) + \frac{H_{32}}{H_{12}} \left(\frac{1-H_{12}}{2+H_{12}} \right) \frac{d\delta_1}{ds}}{\frac{\delta_1}{H_{12}} \frac{dH_{32}}{dH_{12}} + \frac{H_{32}\delta_1}{H_{12}^2} \left(\frac{1-H_{12}}{2+H_{12}} \right)} \right] \\ \frac{dU_v}{ds} &= \frac{U_v H_{12}}{\delta_1 (2+H_{12})} \left[\frac{c_f}{2} - \frac{1}{H_{12}} \frac{d\delta_1}{ds} + \frac{\delta_1}{H_{12}^2} \frac{dH_{12}}{dH_{32}} \frac{dH_{32}}{ds} \right]\end{aligned}\tag{2}$$

where U_v is the "viscous" or inverse velocity. These two equations are entirely equivalent to Eqs. (1a,b), but are turned "inside out" to reflect the switching roles of dependent and independent variables between a weakly interacting flow, where the inviscid solution determines the boundary-layer solution, and a strongly

interacting flow, where the opposite is true. As explained below, convergence is achieved when $U_i = U_v$ everywhere.

For separated flow, also the inverse boundary-layer equations require closure correlations. The most popular choice has been to use the reversed Falkner-Skan profiles as, for instance, was done in Ref. 6. The laser-Doppler anemometer (LDA) measurements inside the bubble described in Ref. 7, however, indicate that the reversed Falkner-Skan profiles are not a good representation of the separated shear layer in the laminar part of the bubble. Rather, Fitzgerald and Mueller suggest using the two-parameter, reversed Green profiles, which were originally developed to model the turbulent wake downstream of a blunt trailing edge. This fact is not surprising once we realize that the separated flow in the laminar part of a short bubble is near-stagnant and, therefore, causes very small negative skin friction. These findings were confirmed by a finite-difference calculation performed by Drela⁸, who found profiles very similar to the Green. From these profiles Drela was able to derive a closure correlation for the skin-friction coefficient, which is used also here, since the Green profiles have zero skin friction by definition:

$$Re_{\delta_2} \frac{c_f}{2} = \begin{cases} -0.07 + 0.0727 \frac{(5.5 - H_{12})^3}{H_{12} + 1}, & H_{12} < 5.5 \\ -0.07 + 0.015 \left(1 - \frac{1}{H_{12} - 4.5}\right)^2, & H_{12} \geq 5.5 \end{cases} \quad (3)$$

where

$$Re_{\delta_2} = \frac{U_v \delta_2}{\nu} \quad (4)$$

is the local Reynolds number based on momentum thickness and the kinematic viscosity $\nu = \mu / \rho$ is the ratio of air viscosity to its density.

As discussed in full in Refs. 2 and 9, the Green profiles are determined by the two parameters G and h/b , where G is the amplitude of Coles's "wake" function for the Green profiles and a measure of the amount of backflow and h/b is the ratio of the height of the bottom of the shear layer above the wall to the width (thickness) of the shear layer. A schematic of a Green profile is shown in Fig. 1. As may be expected, the greater flexibility afforded by the two parameters also brings added complexity in determining adequate closure correlations. Because one of the closure correlations is a new and important addition to the overall model, it is helpful to include a few more details of the derivation here than would otherwise be required.

By integrating the definitions for the integral thicknesses, the following relationships are easily derived:

$$\begin{aligned} \frac{\delta_1}{b} &= G \left(1 + 2 \frac{h}{b}\right) \\ H_{12} &= \frac{1 + 2 \frac{h}{b}}{1 - \frac{3}{2}G + 2 \frac{h}{b}(1 - 2G)} \\ H_{32} &= \frac{2 - \frac{9}{2}G + \frac{5}{2}G^2 + 4 \frac{h}{b}(1 - 3G + 2G^2)}{1 - \frac{3}{2}G + 2 \frac{h}{b}(1 - 2G)} \end{aligned} \quad (5)$$

Although the normalized definition of the Green profiles requires only two parameters, matching them to a developing shear layer makes it necessary to scale both to the same length units. As Eq. (5a) shows, the displacement thickness can be related to the two parameters only after being normalized relative to the shear-layer thickness, b . This brings the number of effective new variables to be accounted for from two to three. Consequently, it is not sufficient to eliminate G and h/b between the above three equations to derive the closure correlation between the shape factors since δ_1/b would remain a part of the correlation. The downstream development of b would require an additional equation, derived empirically or theoretically, to close the system.

In the absence of an additional theoretical relation to invoke, we have decided to utilize the scarce experimental data available to best advantage. Accordingly, the data of Ref. 7 suggest a new correlation between the shape factors, as shown in Fig. 3. The data themselves are not shown since they fall in absolute value somewhat below the valid range of values attainable by H_{32} in the model. This figure shows how the Falkner-Skan locus veers toward velocity profiles characterized by shear layers that are relatively close to the airfoil surface (low h/b) and by fairly large amounts of backflow (high G). The measurements, conversely, point to a shear layer progressively farther from the surface (high h/b) and with a decreasing amount of backflow ($G \rightarrow 0.50$). To reflect this behavior, the solid curves indicate the correlation presently employed:

$$H_{12} = AH_{32}^3 + BH_{32}^2 + CH_{32} + D \quad (6)$$

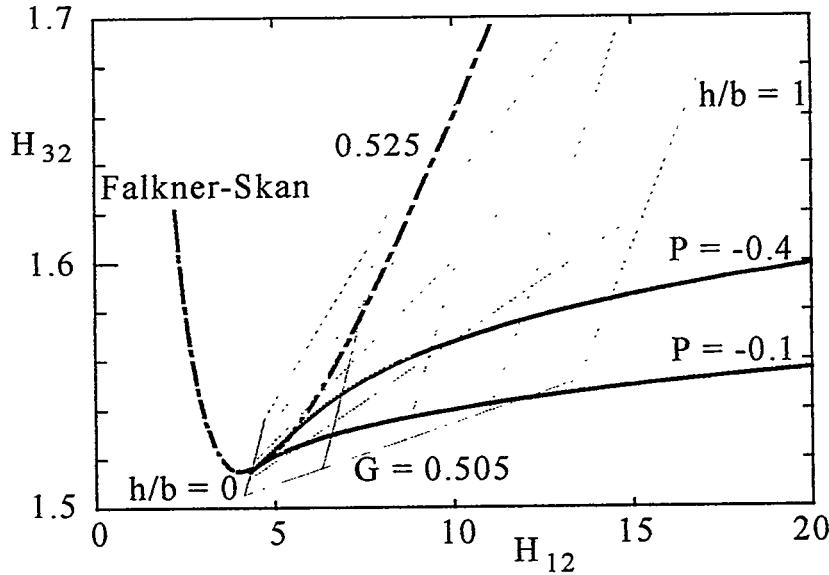


Fig. 3. Comparison between the shape-factor correlation for the Falkner-Skan velocity profiles and the one employed in the present method, shown for two values of P .

Because of the very different ranges of the two shape factors, it is better to employ double precision in solving for the coefficients of this cubic passing through the following points, rather than writing them out here to sixteen decimals:

$$\begin{aligned} \{H_{32}, H_{12}\}_1 &= \{K, 30\} \\ \{H_{32}, H_{12}\}_2 &= \{(H_{32})_s, (H_{12})_s\}, \quad \left(\frac{dH_{12}}{dH_{32}}\right)_2 = 30 \\ \{H_{32}, H_{12}\}_3 &= \{(H_{32})_s - [K - (H_{32})_s], (H_{12})_s - [30 - (H_{12})_s]\} \end{aligned} \quad (7)$$

where

$$\begin{aligned} K &= 1.55 - 0.10P \\ (H_{32})_S &= 1.515095 \\ (H_{12})_S &= 4.3223 \end{aligned} \quad (8)$$

and P is Gaster's pressure gradient parameter¹⁰, given by

$$P = \frac{(\delta_2)_S^2}{\nu} \frac{\Delta U_i}{\Delta s} = Re \left[\frac{(\delta_2)_S}{c} \right]^2 \frac{\Delta(U_i/U_\infty)}{\Delta(s/c)} \quad (9)$$

The subscript S indicates the laminar separation point, U_∞ is the freestream velocity, the Δ 's indicate the average inviscid velocity gradient between laminar separation and turbulent reattachment, and Re is the chord Reynolds number,

$$Re = \frac{U_\infty c}{\nu} \quad (10)$$

The reliance on Gaster's P is motivated by its success at correlating many different properties of the bubble, as discussed more fully in Refs. 2 and 10. The absolute value of P , which is always negative, is lower for leading-edge bubbles and higher for mid-chord bubbles, at a given Reynolds number.

Once both shape factors are known, the two parameters are found from Eqs. (5b,c), since they are needed by the transition prediction method:

$$\begin{aligned} G &= \frac{3(H_{12}-1)}{4H_{12}} - \frac{1}{4H_{12}} \sqrt{9(H_{12}-1)^2 - 8H_{12}(H_{12}+H_{32}-3)} \\ \frac{h}{b} &= -\frac{1-H_{12}(1-1.5G)}{2[1-H_{12}(1-2G)]} \end{aligned} \quad (11)$$

Finally, the closure correlation for the dissipation coefficient for the Green profiles is

$$R_{\delta_2}[C_D]_G = \frac{\pi^2 G^3}{2} \left[1 - \frac{3}{2}G - \frac{(4-5G)(1-G) - (2-3G)H_{32}}{4(1-G) - 2H_{32}} \right] \quad (12)$$

Here an additional empirical function was found necessary. It was observed that at high angles of attack the laminar part of the bubble recovers a great deal of pressure before reaching transition, but this effect was not achieved with the model as described up to now. As the behavior of tufts glued to the airfoil surface in wind-tunnel flow visualisations indicate a fairly vigorous mixing inside short leading-edge bubbles, we postulate a greater entrainment than is found with the laminar part of mid-chord bubbles. The dissipation coefficient actually used in the model, therefore, is modulated by an additional function of P :

$$C_D = \{1.3 - 0.3 \tanh[-40(P + 0.12)]\} [C_D]_G \quad (13)$$

Transition

Transition is modelled by means of the linear stability, or e'' , method described in Ref. 9. This method relies on a database of stability characteristics of the Falkner-Skan profiles for attached flow and of the Green profiles for separated flow, and therefore provides a transition prediction method fully compatible

and consistent with the boundary layer method and with the bubble model. Unless otherwise noted, in the results below the value of the amplification factor used at transition is $n = 11$.

Turbulent Part of Boundary Layer and Separation Bubble

The turbulent boundary layer is taken from Refs. 6 and 8, with only one modification. This method relies on equations equivalent to Eqs. (2a,b) although in a slightly different form, plus an additional equation for the turbulent shear stress coefficient. This third equation serves to model the response lag of the turbulence intensity to rapidly changing streamwise conditions. An example of such non-equilibrium conditions is the reattachment process of the bubble, which involves a very steep pressure rise over a very short streamwise distance followed by a fairly mild gradient. "Equilibrium" here refers to a momentum balance, at a single streamwise location, between the entrainment rate of the outer flow momentum by the turbulence and the consequent rate of pressure rise achieved by the boundary layer. Thus, a non-equilibrium condition may imply, for example, a greater turbulence intensity than the required local rate of pressure rise. The excess energy present in the boundary layer in such a case is not lost, in this method, but affects the growth of the turbulent shear stress coefficient which can carry the extra energy downstream, thereby providing a "history effect" and a more accurate calculation.

The only difference between the present turbulent boundary-layer method and that of Refs. 6 and 8 lies in the manner in which the initial value of the turbulent shear stress coefficient, C_τ , is assigned. Having realized the fundamental importance of this variable to the reattachment process of the bubble, we have made its initial value more easily correlatable to the bubble bursting condition. In Ref. 8 the initial value of C_τ is given by

$$C_\tau = F_\tau^2 C_{\tau,EQ}$$

$$F_\tau = 1.8 \exp\left(\frac{-3.3}{(H_{12})_T - 1}\right) \quad (13)$$

where $C_{\tau,EQ}$ is the equilibrium value of the shear stress coefficient, or the value dependent on the local boundary-layer properties. We have found the following expression more helpful:

$$F_\tau = 0.2 + \left[1.5 + \left(\frac{h}{b}\right)_T\right] \exp\left[\frac{0.14}{P}\right] \quad (14)$$

where the subscript "T" indicates conditions at transition. The rationale here is that thicker bubbles should develop a more energetic turbulent shear layer that reattaches more rapidly. This function has enabled the modelling of both thick, mid-chord bubbles as well as thin, leading-edge bubbles and their bursting, as will be shown below.

Inviscid Vortex

The present formulation of the inviscid vortex is unchanged from that of Ref. 3. However, the function that determines the strength of the vortex has been modified somewhat:

$$\Gamma_v = \begin{cases} 0.08 + 0.04C, & 0 \leq C \leq 0.7868 \\ \frac{0.11}{C + 0.2}, & C > 0.7868 \end{cases} \quad (15)$$

where we call C the circulation parameter, calculated as the ratio of the circulation integral over the attached part of the downwind-surface boundary layer between stagnation and turbulent separation to the same integral over the separated part:

$$C = \frac{\int_{TS}^{TS} U_v \cdot ds}{(U_v)_{TS} L_{TS}} \quad (16)$$

L_{TS} indicates the extent of turbulent separated flow. Since the velocity is constant in the separated region, the circulation integral in the denominator becomes a simple product. The position of the vortex is fixed to lie along a line through the trailing edge and perpendicular to the chord, at a height calculated from

$$y_v = 0.2 \frac{L_{TS}}{(U_v)_{TS}} \quad (17)$$

This equation implies that the constant of proportionality should have units of velocity, although at this point it is not clear which velocity that should be. Note the self-similarity of the vortex position within separated regions of different sizes.

Interaction Algorithm

The interaction algorithm involves an initial guess at the distribution of displacement thickness with which the inverse velocity is calculated. The same distribution of displacement thickness is used together with this inverse velocity to find the equivalent distribution of transpiration velocity according to the equation,

$$v_n = \frac{d}{ds} (\delta_1 U_v) \quad (18)$$

This transpiration velocity is imposed as a boundary condition on the panels, to find a new inviscid velocity which then can be used to find a new displacement thickness distribution from

$$(\delta_1)_{new} = (\delta_1)_{old} \frac{U_v}{U_i} \quad (19)$$

With this new distribution the iteration cycle starts over and keeps going until the maximum difference between U_i and U_v falls below a prescribed tolerance (approximately 0.05 of freestream for most cases considered below).

Results and Discussion

The reason for including so many mathematical details, above, is that the method we have pieced together over the last several years has come to rely on an increasing number of empirical functions. As most of these functions attempt to model physical behavior not accounted for by standard boundary-layer methods, we felt it was important to lay out all we know and all we have guessed. Although we feel that the main ingredients for predicting 2-D stall and post-stall have now been included in the method, the calibration process is still on-going, and some of the functions given above may vary somewhat as the method is refined. Additionally, at the time of this writing the program is not yet fully automated so that we could not produce complete plots of the aerodynamic characteristics of the airfoils for which data is available. We can, however, discuss several comparisons with measured pressure distributions at several Reynolds numbers.

Fig. 4a shows a relatively low Reynolds number case, 500,000, for the NASA NLF(1)-1015 airfoil. In order to match the experimental bubble length better, we used a somewhat higher value of n for this case. The correlations and empirical functions we have developed will have to be better tuned to variations in Reynolds number, although some Reynolds number effect is already embodied in the pressure gradient parameter P . The laminar separation, transition, and reattachment points are labelled on the pressure distribution. Fig. 4b shows the same airfoils at $Re = 2,000,000$ and 12 deg. Here the agreement is very good, both for the small laminar bubble on the leading edge as well as for the large turbulent separated region over the rear of the airfoil, recognizable by the constant pressure.

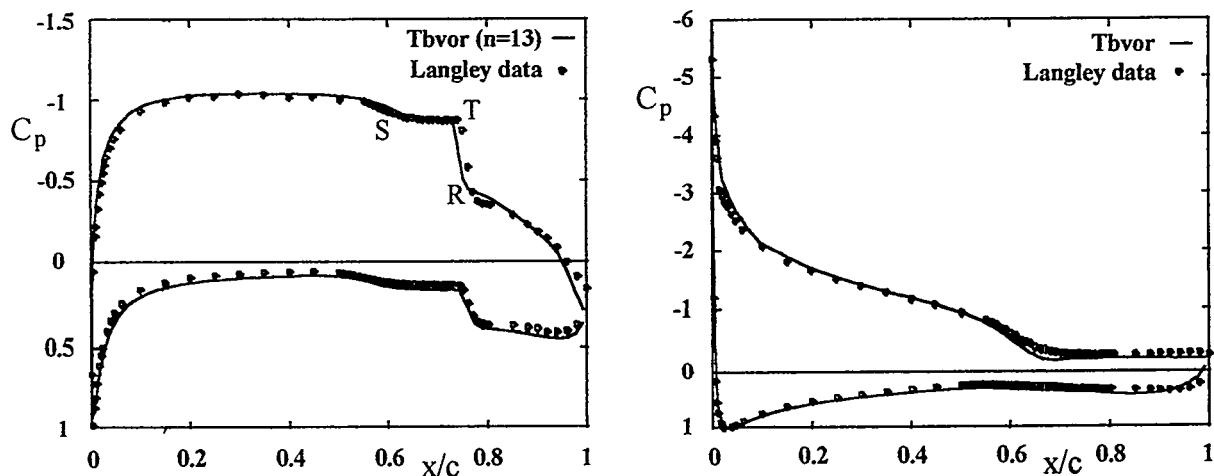


Fig. 4. Comparison of measured and predicted pressure distribution around the NLF(1)-1015 airfoil at $Re = 500,000$, 2 deg., and at $Re = 2,000,000$, 12 deg. Data are from Ref. 11.

In order to see the details of the pressure distribution over the leading-edge bubble more clearly, Fig. 5 shows the pressure over the S809 airfoil at $Re = 2,000,000$ and 18 deg. together with a stretched version of the same plot. The pressure recovery in the turbulent part of the bubble is greater than what the measurements show, and that is most probably why the turbulent separation location is predicted somewhat too soon. Nonetheless, the prediction is very close.

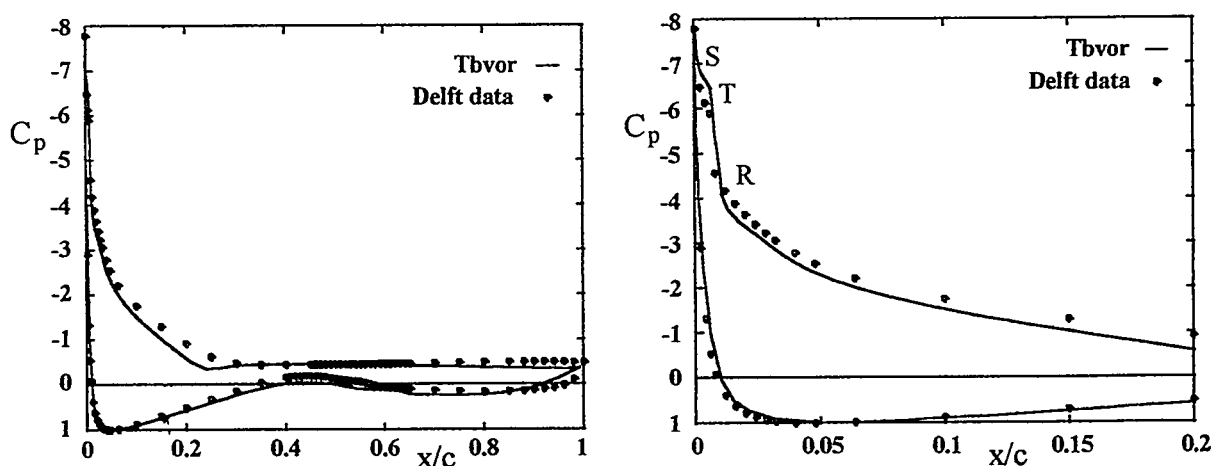


Fig. 5. Comparison of measured and predicted pressure distribution around the S809 airfoil at $Re = 2,000,000$ and 18 deg., and detail of leading-edge laminar separation bubble. Data are from Ref. 12.

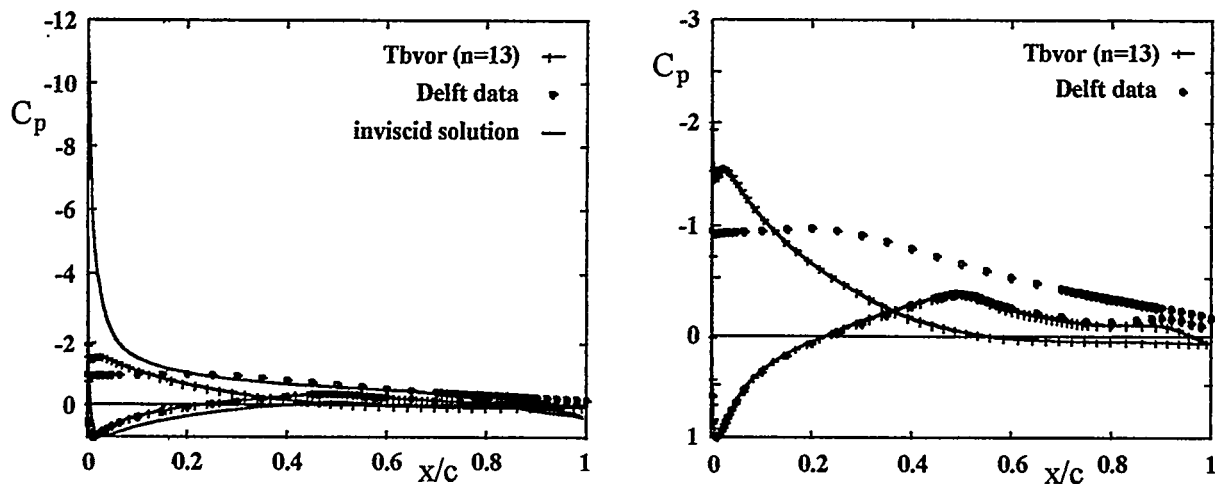


Fig. 6. Comparison of predicted, measured, and inviscid pressure distribution around the S805 airfoil at $Re = 1,000,000$ and -10 deg, and closer view. Data are from Ref. 13.

Finally, Fig. 6 points to possibly another important insight. In order to verify the robustness of the program and its ability to detect the bursting of laminar separation bubbles, we analyzed the most drastic case for which we have reliable experimental data, the S805 airfoil at $Re = 1,000,000$ and -10 deg. As Fig. 6a shows, Tbvor is capable of handling extremely sharp suction peaks and of bringing them down to the level of the experimental pressure. This occurs due to the very fine resolution afforded by the addition and redistribution of points in the regions of the bubbles, as shown by the crosses. Such fine resolution can detect the bursting of the leading-edge bubble without causing the numerical method to become unstable. The predicted point of reattachment of this long bubble is just before 40% c , so it is definitely a “long” bubble. Fig. 6b, however, shows that the agreement on the lower surface is not good. Changing the various parameters of this model did not help bring the shape of the predicted pressure distribution closer to the measurements. This situation is strongly reminiscent of what we encountered when attempting to model the turbulent separated region over the trailing edge. Indeed, also in the present case we are dealing with a turbulent separated region, since transition still occurs within a couple of percent points from the leading edge. It is quite possible that a vortex, this time clockwise (for the upper surface), is the last missing piece of the puzzle for modelling such extreme flowfields. A 40% -long bubble would easily accommodate such a vortex, which we know to be present from flow visualizations, and it would have the global effect required to affect the pressure distribution over the whole stalled surface of the airfoil. In particular, a counterclockwise vortex placed near the lower surface at $0.20\ c$ would slow down the leading-edge flow, driving the predicted pressure closer to the measurements.

Conclusions

The capabilities added to Tbvor over the last year, a fully interactive laminar separation bubble model, the reliance of the bubble on Gaster’s pressure gradient parameter, and point splicing for higher resolution, have proven essential for analyzing any airfoil through post-stall conditions and for detecting bubble bursting. While the overall method is still being calibrated, the comparisons shown demonstrate that all the relevant physical phenomena have been accounted for. Finally, the predictions seem to point to the last missing component of a deep-stall flowfield: the vortical character of a burst leading-edge bubble.

Acknowledgements

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PERFORMANCE AND WAKE PREDICTIONS OF HAWTS IN WIND FARMS

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ABSTRACT

The present contribution proposes and describes a promising way towards performance prediction of an arbitrary array of turbines. It is based on the solution of the time-averaged, steady-state, incompressible Navier-Stokes equations with an appropriate turbulence closure model. The turbines are represented by distributions of momentum sources in the Navier-Stokes equations. In this paper, the applicability and viability of the proposed methodology is demonstrated using an axisymmetric implementation. The $k-\epsilon$ model has been chosen for the closure of the time-averaged, turbulent flow equations and the properties of the incident flow correspond to those of a neutral atmospheric boundary layer. The proposed mathematical model is solved using a Control-Volume Finite Element Method (CVFEM). Detailed results have been obtained using the proposed method for an isolated wind turbine and for two turbines one behind another. In the case of an isolated turbine, accurate wake velocity deficit predictions are obtained and an increase in power due to atmospheric turbulence is found in agreement with measurements. In the case of two turbines, the proposed methodology provides an appropriate modelling of the wind-turbine wake and a realistic prediction of the performance degradation of the downstream turbine.

1. INTRODUCTION

The aerodynamic analysis of Horizontal-Axis Wind Turbines (HAWTs) in wind farms is a challenging problem that involves unsteady aerodynamics, interference and wake effects, atmospheric turbulence, and turbulence generated by the turbines. Reductions in the cost of energy produced by a wind farm can be realized by optimizing the positioning and density of the wind turbines. This optimization process can be successfully achieved using numerical simulations only when reliable mathematical models are used to predict the aerodynamics inside a wind farm. Such mathematical models should have the capabilities of modelling the atmospheric boundary layer as well as the wind turbine action on the flowfield and the interference effects between the turbines.

Past studies were mainly concerned with the prediction of the wake of a single turbine, which is of considerable interest because the velocity deficit introduced by a turbine will significantly affect the performance of the downstream turbines. In the wake recovery process, both atmospheric and rotor-induced turbulence play a significant role. The modelling of such a turbulent flow is complicated by the coexistence of small- and large-scale turbulent structures and also by the complexity of the problem: a complete simulation would indeed need to be three-dimensional, unsteady and should compute the flowfield velocities, pressure, temperature and turbulent properties.

In 1974, Templin [1] proposed a simple, but efficient model to predict the effect of turbine spacing on the power output of wind parks. His analysis consisted in modelling the wind park as a distributed roughness due to the drag of the turbines. Such an analysis is restricted to an "infinite" array of turbines so that the predicted minimum spacing should be considered as an upper bound [2]. Based on jets analysis, Lissaman [3] represented the wake of a turbine in three different regions: the initial wake region, the transition zone and the fully developed wake region. For each region, self-similar

profiles are used in conjunction with the assumption of momentum-deficit conservation to obtain the velocity distribution. This assumption is valid only for unbounded flows. Furthermore, the wakes from the turbines are simply superimposed to determine the velocity at any point in the array. Therefore, the interferences between the wakes are assumed to be negligible. More recently, Ainslie [4] and Crespo et al. [5] proposed to solve the Navier-Stokes equations to simulate the rotor wakes. The turbulence closure model used by Ainslie is an algebraic eddy-viscosity-based model while Crespo used the k - ϵ model [6]. However, their formulations were restricted to the wake region and neither the wake effects on the downstream turbine, nor the performance of the turbine producing the wake could be computed.

A more general model is under development at Ecole Polytechnique de Montréal. Masson et al. [7] have used a CVFEM method [8] to solve the Navier-Stokes equations for the flow over an isolated wind turbine. This first attempt has led to a two-dimensional axisymmetric method where the flow properties have been averaged over a period of rotation of the rotor. The rotor is represented by a distribution of momentum source whose magnitude is evaluated using blade-element theory. This approach has given good power predictions for a single turbine and can be used to predict the velocities in the wake, including swirl. However, Masson et al. [7] were assuming the flow to be laminar, and thus the predicted wake recovery was not realistic. This paper deals with the implementation of the k - ϵ model in the approach of Masson et al. [7] in order to simulate the actual turbulent flow around a wind turbine. The set of equations to be solved is first presented with the relations for the velocities, kinetic turbulent energy and dissipation in the atmospheric boundary layer. The modelling of the rotor and the CVFEM method are then briefly reviewed. Finally, results are presented for the case of the TNO wind turbine model [9] and for the MOD-0A [10] rotor for which experimental results were available. These comparisons illustrate the capability of the k - ϵ model to take into account both the ambient and wake shear-generated turbulence.

2. DESCRIPTION OF THE BASIC FLOW

The flow upstream of the rotor is the one observed in the first hundred meters of the atmospheric boundary layer, over uniform flat terrain in the case of neutral conditions (temperature decreasing upward at the isentropic rate). The expressions describing this flow are taken from Panofsky and Dutton [11].

The turbulent viscosity is given by the mixing length relation:

$$\nu_{t0}(z) = K u_* z \quad (1)$$

where K is the von Karman constant ($K=0.4$) and z is the vertical coordinate ($z=0$ at the ground). The turbulent friction velocity u_* is given by:

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \quad (2)$$

where τ_0 is the surface shear stress and ρ , the air density. Assuming the shear stress to be constant over the lower part of the atmospheric boundary layer, a logarithmic velocity profile is obtained:

$$u_0(z) = \frac{u_*}{K} \ln \left(\frac{z}{z_0} \right) \quad (3)$$

where z_0 corresponds to the roughness length of the site and x to the coordinate in the windward direction.

Assuming equilibrium between production and dissipation of turbulent kinetic energy, one can find:

$$\epsilon_0(z) = \frac{u_*^3}{Kz} \quad (4)$$

Finally, making use of the k - ϵ model [6], a relation between the turbulent kinetic energy k and ϵ is obtained:

$$k_0(z) = \sqrt{\frac{\nu_{t0}\epsilon_0}{C_\mu}} \quad (5)$$

3. GOVERNING EQUATIONS

Using the eddy-viscosity concept, the mean-flow equations are given by:

$$\nabla \cdot (\rho \vec{V}) = 0 \quad (6)$$

$$\nabla \cdot (\rho \vec{V} \vec{V}) = \nabla(\rho \nu_t (\nabla \vec{V} + \nabla^t \vec{V})) - \nabla p + \rho \vec{g} + \vec{f}_{WT} \quad (7)$$

where $\vec{f}_{WT}$ are the body forces per unit volume of the fluid and represent the effects of the rotor on the flowfield. The molecular viscosity has been neglected, as it is assumed to be much smaller than its turbulent counterpart ν_t .

3.1 Modelling of the rotor

The effects of the rotor on the flow are averaged over a period of rotation of the blade in the same manner as in momentum-strip theories. The forces exerted by the rotor on the flow are modelled as source terms [12] in the x , r , and θ momentum equations and are calculated using blade-element theory. The interested reader is referred to the work of Masson et al. [7] for the derivation of the source terms representing the rotor and for their implementation in the governing equations.

3.2 Turbulence modelling

A turbulence model is needed in order to close the above system of time-averaged equations. Atmospheric, wake shear-generated and blade-generated (viscous effects due to the blades) turbulence are the three major contributions to turbulence in the wake of a wind turbine. Various experiments have demonstrated that in the first two diameters downstream of a rotor, strong turbulence is generated by the degradation of tip vortices and by shear production [13]. Further downstream, turbulence properties recover their upstream values and thus, atmospheric turbulence controls the growth of the wake.

To account for turbulence, Liu et al. [14] have used the undisturbed atmospheric turbulence properties for their calculations, which seems reasonable if one considers the relatively small region of influence of the rotor-induced turbulence. However, this approach is not fully appropriate since the wake recovery process is highly influenced by the early stage of wake development. Therefore, a model taking both shear-generated and atmospheric turbulence into account is a minimum requirement. Simple algebraic models [4] meet this requirement but they assume balance between production and viscous dissipation of turbulent kinetic energy. Such an hypothesis is not valid in the immediate downstream vicinity of the rotor, where production of turbulent kinetic energy largely exceeds its dissipation. Two-equation model are more appropriate for this type of flow. In this work, the k - ϵ model [6] has been selected mainly because of its wide use and because of the availability of k and ϵ properties of atmospheric boundary layers in meteorological data.

Standard equations for the k - ϵ model are:

$$\nabla \cdot (\vec{V}k) = \nabla \cdot \left(\frac{\nu_t}{\sigma_k} \nabla k \right) + \nu_t (\nabla \vec{V} + \nabla^t \vec{V}) : \nabla \vec{V} - \epsilon \quad (8)$$

$$\nabla \cdot (\vec{V}\epsilon) = \nabla \cdot \left(\frac{\nu_t}{\sigma_\epsilon} \nabla \epsilon \right) + C_{\epsilon 1} \frac{\epsilon}{k} \nu_t (\nabla \vec{V} + \nabla^t \vec{V}) : \nabla \vec{V} - C_{\epsilon 2} \frac{\epsilon^2}{k} \quad (9)$$

$$\nu_t = C_\mu \frac{k^2}{\epsilon} \quad (10)$$

The values for the closure coefficients are:

$$C_{\epsilon 1} = 1.24 \quad C_{\epsilon 2} = 1.92 \quad C_\mu = 0.033 \quad \sigma_k = 1.0 \quad \sigma_\epsilon = 1.3 \quad (11)$$

The values of C_μ and $C_{\epsilon 1}$ have been changed from those in the original model of Jones and Laund-
er [6], in order to satisfy the system of equations for the neutral atmosphere case [5].

3.3 Derivation of an axisymmetric formulation

For the case of a rotor immersed in the atmospheric boundary layer, let ϕ , one of the dependent properties of interest (i.e. $\phi = \vec{V}, p, k$ or ϵ), be expressed as:

$$\phi(x, y, z) = \phi^*(x, y, z) + \tilde{\phi}_0(z) \quad (12)$$

where $\tilde{\phi}_0(z) = \phi_0(z) - \phi_0(h)$, $\phi_0(z)$ corresponds to the undisturbed atmospheric boundary layer (see Eqs.(3) to (5)) and $\phi_0(h)$ to the value of the dependent property of the undisturbed flow at the hub height h . Therefore, ϕ^* represents the sum of the perturbation of ϕ due to the presence of the rotor plus the value of $\phi_0(z)$ evaluated at the hub height.

In this work, it is assumed that the variations of the properties of the undisturbed atmospheric boundary layer (ϕ_0) in the immediate vicinity of the turbine are negligible with respect to the variations of the perturbation flow ϕ^* , i.e. :

$$\tilde{\phi}_0 \ll \phi^* \quad (13)$$

$$\nabla \tilde{\phi}_0 \ll \nabla \phi^* \quad (14)$$

It is to be noted that these assumptions are strictly valid only when $\frac{h}{R} \gg 1$ where R is the radius of the wind turbine under study.

Using these proposed simplifications, and subtracting the undisturbed-flow terms from the continuity, momentum and $k - \epsilon$ equations, the following governing equations are obtained for the perturbation flow properties $\vec{V}^*, p^*, k^*$ and ϵ^* :

$$\nabla \cdot (\rho \vec{V}^*) = 0 \quad (15)$$

$$\nabla \cdot (\rho \vec{V}^* \vec{V}^*) = \nabla (\rho \nu_t^* (\nabla \vec{V}^* + \nabla^t \vec{V}^*)) - \nabla p^* + \vec{f}_{WT} \quad (16)$$

$$\nabla \cdot (\vec{V}^* k^*) = \nabla \cdot \left(\frac{\nu_t^*}{\sigma_k} \nabla k^* \right) + \nu_t^* (\nabla \vec{V}^* + \nabla^t \vec{V}^*) : \nabla \vec{V}^* - \epsilon^* + \epsilon_0(h) \quad (17)$$

$$\nabla \cdot (\vec{V}^* \epsilon^*) = \nabla \cdot \left(\frac{\nu_t^*}{\sigma_\epsilon} \nabla \epsilon^* \right) + C_{\epsilon 1} \frac{\epsilon^*}{k^*} \nu_t^* (\nabla \vec{V}^* + \nabla^t \vec{V}^*) : \nabla \vec{V}^* - C_{\epsilon 2} \frac{\epsilon^{*2}}{k^*} + C_{\epsilon 2} \frac{\epsilon_0^2(h)}{k_0(h)} \quad (18)$$

$$\text{where } \nu_t^* = C_\mu \frac{k^{*2}}{\epsilon^*}$$

Far upstream and downstream of the wind turbine, the properties of the flow (ϕ) are those of the basic undisturbed flow (ϕ_0), and thus, the perturbation properties $\vec{V}^*, k^*$ and ϵ^* are equal to $\vec{V}_0(h)$, $k_0(h)$ and $\epsilon_0(h)$. The system of equations for the perturbation flow (Eqs.(15) to (18)) has then the remarkable property that, if the turbine source term $\vec{f}_{WT}$ is axisymmetric, the solution in $\vec{V}^*, k^*$ and ϵ^* will also be axisymmetric. In this work, the assumption of axisymmetric $\vec{f}_{WT}$ is used.

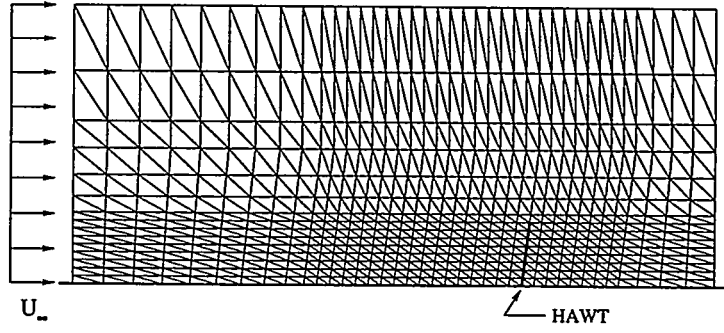


Fig. 1: Computational Domain and Grid Topography

4. NUMERICAL METHOD

The proposed numerical method is a CVFEM based on the primitive-variables, co-located, equal-order formulation of Masson et al. [8]. Aspects relevant to the successful simulation of the flow around a wind turbine are presented in Ref. [7]. The interested reader is referred to these articles for further information.

The computational domain is a simple cylinder that includes the wind turbine. A schematic of the grid topography used for the simulations is presented in Fig. 1. It is to be noted that the actual grids used are much finer than the one shown here. Boundary conditions for $\vec{V}^*$, k^* , ϵ^* have to be prescribed at the three faces of this cylindrical domain:

Inlet Boundary: The inlet boundary is a $r - \theta$ plane located upstream of the wind turbine. In this plane, the three velocity components and $k^* - \epsilon^*$ properties are given by the values of the undisturbed neutral atmospheric boundary layer properties at the hub height ($\vec{V}_0(h)$, $k_0(h)$ and $\epsilon_0(h)$).

Outlet Boundary: The outlet boundary is a $r - \theta$ plane located downstream of the wind turbine. In this plane, the three velocity components and $k^* - \epsilon^*$ properties are computed from the discretised equations obtained using the outflow treatment of Patankar [15].

Top Boundary: This is a curved surface located at a radial distance far from the wind turbine blade tip. In this plane, the velocity is set to its undisturbed value at the hub height $\vec{V}_0(h)$ and the diffusion of turbulent kinetic energy and rate of viscous dissipation is set to zero.

5. RESULTS

In order to estimate the capability of the $k-\epsilon$ model to predict the flow properties of wakes, the turbulent wake of a body of revolution has been simulated numerically. The resulting numerical solutions are compared to the experimental data of Chevray [16]. The experiments consist in a six-to-one spheroid immersed in a flow with a Reynolds number (based on the length of the body) of $2.75 \cdot 10^6$. A 35×40 grid was used and initial conditions for the simulations were taken from the measurements of Chevray at an axial distance of three diameters downstream of the body. In Fig. 2, the normalized centreline velocity deficit is plotted as a function of the normalized axial position. The $k-\epsilon$ model gives reasonably good predictions with a small departure from the experiments far downstream of the body. It is to be noted however that a theoretical analysis based on similar solutions [16] predicts that the velocity deficit should vary with $(x - x_0)^{-2/3}$, which is in perfect agreement with the logarithmic slope of -0.67 derived from our computations.

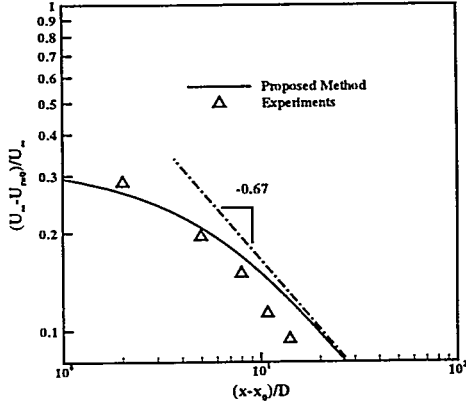


Fig. 2: Centreline Velocity Deficit versus Axial Position , $\frac{x_0}{D} = 4$

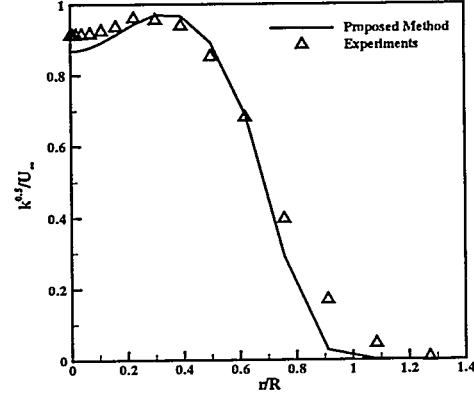


Fig. 3: Distribution of Radial Turbulence Intensity for $\frac{x}{D} = 18$

The predicted radial distribution of the kinetic turbulent energy at eighteen diameters downstream of the body of revolution is presented in Fig. 3 and compared with the experimental measurements. The agreement is very good and this comparison demonstrates the capability of the $k-\epsilon$ model to predict wake flows.

In Fig. 4, the predicted axial distribution of the centreline velocity deficit for the case of the TNO wind-turbine model [9] is compared to experimental observations. The experimental device consists of a 36-cm-diameter rotor located at a height of one diameter from the ground in a simulated atmospheric boundary layer with a roughness length of 0.04 cm. Far upstream from the rotor, the velocity at the hub height is 9.7 m/s. The velocity gradients of the undisturbed flow are consequently very large in the vicinity of the rotor, as are the gradients of turbulent kinetic energy and dissipation. Therefore, the assumptions introduced to obtain an axisymmetric formulation (see Eqs.(13)-(14)) are not valid in this flow. However, this case has been represented numerically in the following way:

- The upstream properties of the flow are uniform and their values are those of the simulated atmospheric boundary layer at the hub height (i.e. $u = U_\infty = 9.7$ m/s).
- For turbulence closure, the eddy viscosity is set to a constant value corresponding to the eddy viscosity of the neutral undisturbed atmospheric boundary layer at the hub height.
- The inlet boundary of the calculation domain is located just downstream of the rotor plane of rotation. For $r < R$, the inflow velocity is set to $U_\infty \sqrt{1 - C_T}$, where C_T corresponds to the measured thrust coefficient of the turbine (here, $C_T = 0.74$ [9]). For $r > R$, the inflow velocity is set to U_∞ .

It has been found that grid independent wake decay predictions were reached for a 70x80 grid. In Fig. 4, results of the algebraic eddy-viscosity model (NWAKE) developed by Ainslie [4] are also presented. The proposed method provides a good correlation with the experimental results in the near wake region, while discrepancies are observed in the fully developed wake region. Furthermore, the centreline velocity deficit was found to vary as $x^{-1.0}$ while experiments indicate a logarithmic slope of -1.25.

Results presented in Figs. 5 to 10 are related to the MOD-0A wind turbine (38.1 m in diameter, hub height at 30.5 m) operating at a rotational speed of 40 rpm and a pitch angle of 0 degree.

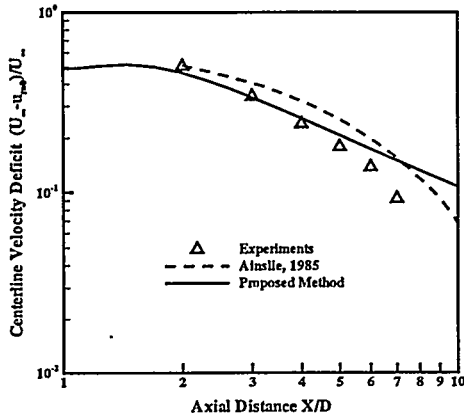


Fig. 4: Decay of the Centreline Velocity Deficit along the Wake of the TNO Wind Turbine Model

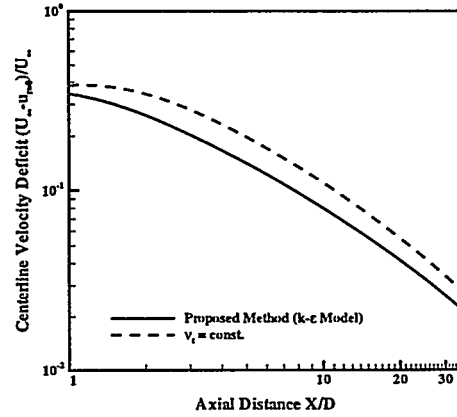


Fig. 5: Decay of the Centreline Velocity Deficit along the Wake of the MOD-0A Wind Turbine

The atmospheric boundary layer is considered to be in neutral conditions and an average value of 0.05m for the roughness length (typical of long grass and rocky ground) is taken.

Fig. 5 presents the centreline velocity deficit along the wake of a MOD-0A wind turbine. The results have been produced with the axisymmetric method presented in the previous sections and an inflow velocity at the hub height of 8.05 m/s. A 132x43 grid is used and 16 control volumes lie along the blade. The inlet boundary is located at 7.5 diameters upstream of the turbine, the outlet boundary at 35 diameters downstream and the top boundary at 4.2 diameters from the axis of rotation. To illustrate the relevance of using the $k-\epsilon$ model, results of a simulation where the eddy viscosity is set to a constant value corresponding to the eddy viscosity of the neutral undisturbed atmospheric boundary layer flow at the hub height (i.e. the eddy viscosity is set by Eq.(1) to $6.13 \text{ m}^2/\text{s}$) are presented in Fig. 5. It is found that wake recovery is achieved earlier when the $k-\epsilon$ model is used. This is an expected result since the turbulent mixing is very high in the immediate downstream vicinity of the turbine and thus, eddy viscosities are higher than those of the undisturbed flow. When the $k-\epsilon$ model is used, it is indeed found that in the near wake region, the predicted eddy viscosity is three times larger than its undisturbed value. The centreline velocity deficit is found to vary as $x^{-1.06}$.

As in the case of the TNO experiments, the proposed model significantly underpredicts the wake centreline velocity deficit recovery far downstream, which has been experimentally observed to vary as $x^{-1.25}$ [17]. However, the recent experiments conducted by Högström [13] indicate a variation of $x^{-1.1}$. It is the authors' opinion that this underprediction is related to the inability of the axisymmetric implementation to represent ground effects. Moreover, neglect of blade-generated turbulence in the present model may also influence the wake recovery: friction on the rotor blades and tip vortex shedding produce turbulent vortices that increase the momentum transfer in the wake.

Fig. 6 shows a diagram of the experimental installation used by Doran et al. [10] to obtain measurements in the wake of a MOD-0A wind turbine. The arrangement consisted of a plane array of 7 towers located 4 diameters southwest of the turbine and of 2 towers placed 4 diameters northeast of the turbine. On each tower, Gill propeller anemometers were installed at the hub height. Comparisons with experimental wake measurements for the MOD-0A wind turbine [10] are presented in Figs. 7 and 8. The two cases selected are those for which the hypothesis of a neutral atmosphere

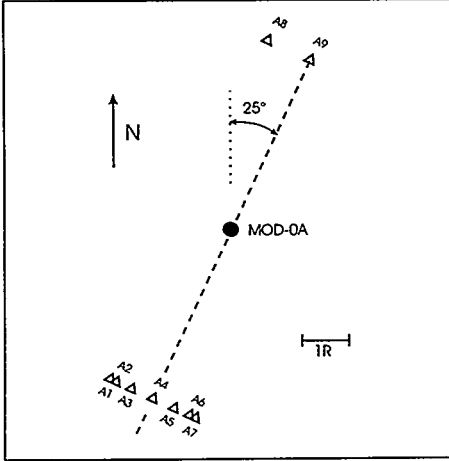


Fig. 6: Schematic Diagram of Turbine and Anemometers Positions

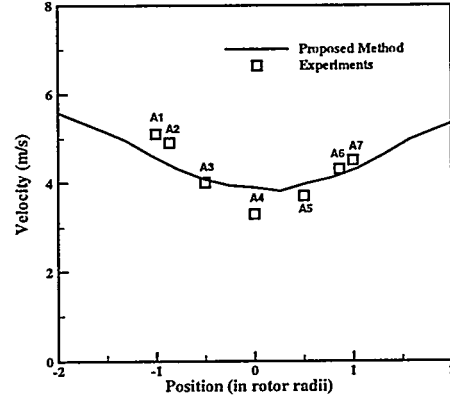


Fig. 7: Comparison of Model Predictions with Experimental Measurements in the Wake of the MOD-0A Wind Turbine, $U_{\infty} = 5.67$ m/s, wind angle= 23°

was the most applicable. Fig. 7 illustrates a comparison between the predicted wake velocities and the experimental measurements for an incident wind speed at the hub height of 5.67 m/s and an incident wind angle of 23° . The abscissa refers to the anemometers position (normalized by the turbine radius) with respect to the rotor position. In Fig. 8, the wind incident angle is 193° and the incident wind velocity is 8.17 m/s. In both cases, satisfactory agreement is achieved.

To further illustrate the capabilities of the proposed method, the effects of turbulence on power performances have been studied. An experimental analysis conducted by Elliott and Cadogan [18] has shown that for a given hub height velocity, an increase in turbulence intensity will lead to an increase in mechanical power produced by the turbine. Theoretically, the power produced by a turbine in a turbulent flow, $\bar{P}$, was quantified as [18]:

$$\bar{P} = P(\bar{u})[1 + 3(\frac{\sigma}{\bar{u}})^2] \quad (19)$$

where $P(\bar{u})$ is the power produced by a turbine in a laminar flow and $(\frac{\sigma}{\bar{u}})$ is the turbulence intensity. In Fig. 9, the computed power of an isolated turbine immersed in a laminar and a turbulent boundary layer are compared. The theoretical power curve predicted by Eq.(19) is also presented. As the turbulent mixing increases the mass flux through the rotor swept area, the relative velocities seen by the blades are higher, and thus it is natural that more power is produced by the turbine in the turbulent situation. However, at large wind velocities, the rotor blades start to enter into stall conditions and then, the rotor performance is less dependent on the incoming flow. The comparison between the results obtained with the proposed method and the theoretical curve is generally good, except for high wind velocities since Eq.(19) does not account for blade stall.

An interesting feature offered by the proposed method is its capability to estimate the performance of two or more turbines one behind another. Fig. 10 shows the results for the case of two MOD-0A wind turbines located one behind another and having the same axis of rotation. The abscissa refers to the spacing between the turbines while the ordinate gives the predicted mechanical power normalized by the power of a stand-alone turbine ($P_{isolated}$). The incoming wind velocity for these computations was 8 m/s. It is worth noticing that the downstream turbine has nearly no effect on the upstream one, except when the turbines are very close to one another ($L/D < 2$). For a spacing

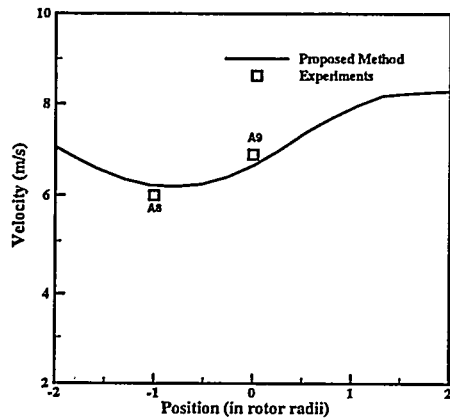


Fig. 8: Comparison of Model Predictions with Experimental Measurements in the Wake of the MOD-0A Wind Turbine, $U_{\infty} = 8.17$ m/s, wind angle = 193°

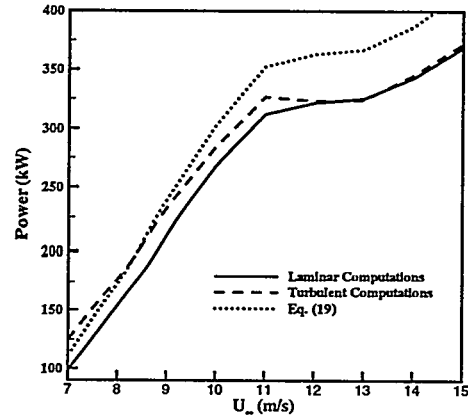


Fig. 9: Mechanical Power Predictions in Turbulent and non-Turbulent Situations for the MOD-0A Wind Turbine

of seven diameters between the turbines, wake effects cause the downstream turbine to produce 80% of the power of a stand-alone turbine, submitted to the same wind conditions.

6. CONCLUSIONS

As a preliminary step towards the development of mathematical models and numerical methods for the optimization of the relative positioning of wind turbines in a wind farm, a 2-D axisymmetric method based on the solution of the time-averaged Navier-Stokes equations with the $k-\epsilon$ model for turbulence closure has been developed and presented in this paper. In this method, wind turbines are represented by distributions of momentum sources. Comparisons between experiments and predictions for a single wind turbine have shown that fairly accurate near-wake velocity predictions are obtained. However, the logarithmic slope of the axial far-wake velocity deficit recovery is underpredicted. This behaviour is not related to the proposed mathematical model, but is thought to be the consequence of the inability of the proposed axisymmetric implementation to take ground effects into account. For a single wind turbine, the effects of atmospheric turbulence on the mechanical power have been studied: an increase in performance compared to the laminar-flow situation was predicted in accordance with measurements. The applicability of the proposed method to wind farm analysis has been demonstrated for the case of two wind turbines one behind another. Realistic performance degradation of the downstream wind turbine has been calculated.

ACKNOWLEDGEMENTS

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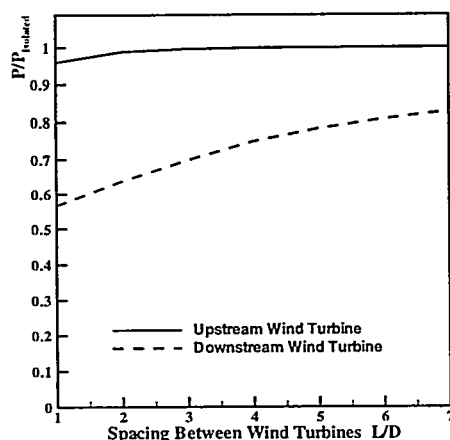


Fig. 10: Performance of Two MOD-0A Wind Turbines one behind another

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AN EVALUATION OF AN EMPIRICAL MODEL FOR STALL DELAY DUE TO ROTATION FOR HAWTS

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ABSTRACT

The objective of this study was to evaluate the Corrigan and Schillings stall delay model for predicting rotor performance for horizontal axis wind turbines. Two-dimensional (2D) wind tunnel characteristics with and without stall delay were used in the computer program PROP93 to predict performance for the NREL Combined Experiment Rotor (CER) and a lower solidity commercial machine. For the CER, predictions were made with a constant-chord/twisted blade and a hypothetical tapered/twisted blade. Results for the constant-chord/twisted blade were compared with CER data. Predicted performance using this empirical stall-delay method provided significant increases in peak power over 2D post-stall airfoil characteristics. The predicted peak power increase due to stall delay for the CER was found to be quite large (20% to 30%) as a result of its high blade solidity. For a more typical, lower-solidity commercial blade the predicted peak power increase was 15% to 20%. As described in the paper, correlation with test data was problematic due to factors not related to the stall-delay model.

INTRODUCTION

The accuracy of blade-element/momentum performance prediction codes such as PROP93 is dependent on the input airfoil characteristics, namely, the lift coefficient (c_l) and drag coefficient (c_d). These airfoil characteristics are typically based on two-dimensional (2D) wind-tunnel measurements that are known to normally underpredict peak power by 10% to 30% as well as the associated blade flapwise bending moment. Experimentally measured airfoil characteristics on rotating blades have found them to be substantially altered over the inboard portion of the blade by three-dimensional (3D) effects due to rotation.¹⁻⁵ These effects result in airfoil maximum lift coefficients ($c_{l,max}$) much larger than 2D measurements. The increase in $c_{l,max}$ has been attributed to centrifugal pumping which is modified by a Coriolis displacement in the chordwise direction.⁶ Blade rotation results in centrifugal-induced outward radial flow in the separated flow region. The radial flow due to rotation develops in the presence of an adverse velocity gradient where the flow is strongly retarded. These effects have been modeled with complex computational fluid dynamics (CFD) methods.^{7,8} For design purposes, simplified empirical methods are needed that capture the first-order effects due to rotation.

Three noteworthy empirical methods with a common basis have provided qualitative predictions and in some cases shown good agreement with experimental results. These methods provide approximations for radial flow modified by a Coriolis displacement that results in stall delay. The radial flow has been found to result from centrifugal force and the radial pressure gradient. Analytical considerations have shown the centrifugal component to be a function of the ratio of local chord to local radius (c/r). The radial pressure gradient has been more difficult to quantify. Eggers and Digumarthi⁹ developed an approximate model to calculate the effects

resulting from centrifugal viscous pumping and the resulting Coriolis displacement associated with deep-stalled flow. Their method relies on 2D wind-tunnel pressure data to calculate inplane and out-of-plane increments that are added to the 2D results. Predictions with this method for the constant-chord, non-twisted Combined Experiment Rotor (CER) blades showed good agreement with power measurements. Corrigan and Schillings⁴ developed a simple method that calculates a stall delay angle for use in modifying the 2D wind-tunnel data. This method accounts for both centrifugal and radial pressure gradient effects and has been used successfully for helicopter rotors and prop-rotors to better predict stall delay effects on rotor loads and performance for high-thrust conditions. Recent work by Snel et al.⁵ also recognized the dependency of stall delay on the blade shape parameter c/r associated with centrifugal/Coriolis effects and the radial pressure gradient. Their results also show a promising basis for predicting the 3D effects due to blade rotation.

The method of Corrigan and Schillings⁴ was chosen for this evaluation because of its simplicity and ability to quantify the influence of centrifugal force and the radial pressure gradient by calculating a stall-delay angle. The stall-delay angle is then used to adjust 2D airfoil data of c_l and c_d which results in greater c_l and a lower c_d . The modified airfoil data can then be used in PROP93 to predict enhanced peak power as a result of blade rotation. Providing that the method of Corrigan and Schillings yields realistic results for wind turbines, designers would then be able to better predict peak power and the associated blade loads.

EMPIRICAL STALL DELAY MODEL

The method of Corrigan and Schillings⁴ and others^{5,9} is based on a shape function or local solidity which relates the stall delay to the ratio of the local blade chord divided by its radial distance (c/r) from the center of rotation as shown in Fig. 1. This representation implies that the centrifugal induced outward flow coupled with a Coriolis displacement is proportional to the ratio of the local c/r and that stall delay increases with local blade solidity. Radial flow reduces the suction surface boundary-layer thickness, the resulting drag, and the associated decambering of the airfoil. The calculations assume an external flow having a linear adverse velocity gradient over the airfoil's suction surface given by Equation 1.

$$u(z \rightarrow \infty) = \Omega r(1 - K\theta) \left[1 - K \left(\frac{c}{r} \right) \right] \quad (1.)$$

The separation point defined by $\partial u / \partial z = 0$, assumed to be at the trailing edge, was determined for a range of velocity gradient (K) values. The separation point is related to the velocity gradient K through the universal curve shown in Fig. 2.

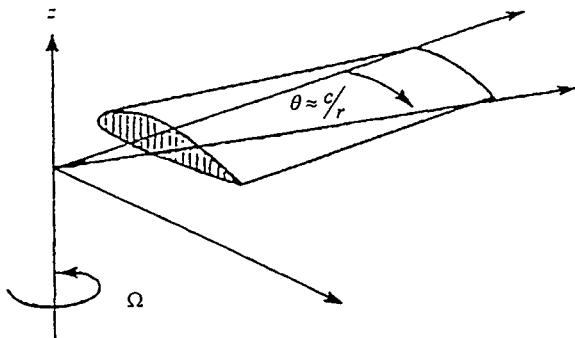


Fig. 1 Coordinate system used by Banks and Gadd (Ref. 6).

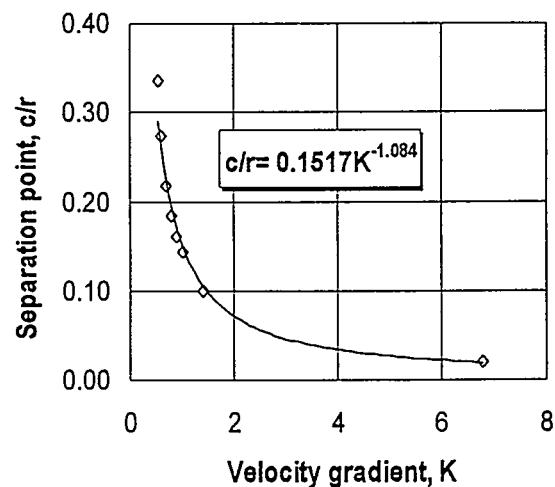


Fig. 2 Relationship for velocity gradient K and the separation point.

While partly based on analytical considerations,⁶ the calculation for the stall-delay angle was largely derived through correlation with helicopter and prop-rotor test data over several years and is given by Equation 2.

$$\Delta \alpha = \left(\alpha_{C_{l,max}} - \alpha_{C_{l=0}} \right) \left[\left(\frac{K \theta_{TE}}{0.136} \right)^n - 1 \right] \quad (2.)$$

Equation (2) can be thought of as the product of an aerodynamic and centrifugal component. The aerodynamic component, the difference between the angle of attack at $c_{l,max}$ and the angle of attack at zero lift, implies that high $c_{l,max}$ airfoils result in a larger radial pressure gradient that contributes to the outboard radial flow which results in more stall delay than low $c_{l,max}$ airfoils. This empirical component was necessary to achieve correlation with helicopter and prop-rotor data sets. The centrifugal component is based on analytical considerations⁶ from the momentum and continuity equations. This component relates to the local blade solidity and implies that greater local solidity and overall blade solidity results in more stall delay due to centrifugal pumping. The strength of the centrifugal term is proportional to the exponent n . For $n=0$, the stall delay becomes zero which is characteristic of 2D data. Corrigan⁴ indicates that n varies from 0.8 to 1.6 to provide correlation with most test data and that $n=1$ provides good results for most cases. Based on this recommendation, $n=1$ was used throughout this evaluation.

APPLICATION TO STALL REGULATED TURBINES

The combined experiment rotor was chosen for verification of the stall delay model due to available test data related to this machine. This includes a 2D-airfoil data set for the machine's NREL S809 airfoil measured by Somers¹⁰ in the Delft University of Technology low-speed wind tunnel. Rotor performance was predicted using PROP93¹¹ with 2D Delft data and with these data modified with the post-stall model. Calculations were done for the CER having constant-chord/twisted blades and a hypothetical tapered/twisted blade similar to one to be fabricated. Predicted results for the constant-chord/twisted blade were compared with measured CER data. Due to its high solidity and low rpm, the CER was not characteristic of most commercial machines. Therefore, the low solidity AWT-26 rotor was also chosen for analysis and comparison with available test data.

CER Rotor Model

The three-bladed CER models used in PROP93 consist of ten radial segments per blade with a root cutout of 20% as seen in Fig. 3. The twist distribution is exponential with most of the twist toward the root. An equivalent tapered planform with the same chord at 80% radius results in a similar peak power as the constant chord blade. Using the Corrigan and Schillings equation, stall delay was calculated from root to tip for the constant chord and tapered planform as shown in Table 1. Relative to the constant chord blade, the tapered blade has a greater amount of stall delay toward the blade root and less toward the blade tip.

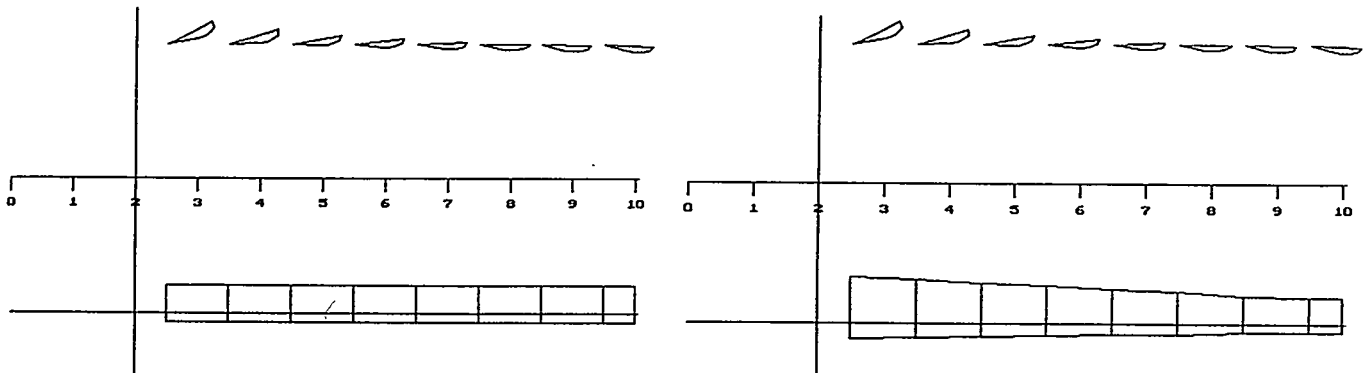


Fig. 3 Combined experiment blade geometries.

Table 1. Constant Chord and Tapered Chord Calculations of Stall-Delay Angle.

r/R	CER	c/R	c/r	K	alfa clma	alfa clzer	del alfa	K*Θ/0.136	delay ang
0.050	0.050	1.000	0.178	9.000	-1.200	10.200	1.307	3.135	
0.150	0.091	0.607	0.281	9.000	-1.200	10.200	1.254	2.588	
0.250	0.091	0.364	0.448	9.000	-1.200	10.200	1.201	2.051	
0.350	0.091	0.260	0.610	9.000	-1.200	10.200	1.168	1.709	
0.450	0.091	0.202	0.768	9.000	-1.200	10.200	1.143	1.461	
0.550	0.091	0.166	0.923	9.000	-1.200	10.200	1.124	1.266	
0.650	0.091	0.140	1.076	9.000	-1.200	10.200	1.108	1.106	
0.750	0.091	0.121	1.226	9.000	-1.200	10.200	1.095	0.971	
0.850	0.091	0.107	1.375	9.000	-1.200	10.200	1.084	0.854	
0.950	0.091	0.096	1.523	9.000	-1.200	10.200	1.074	0.751	

r/R	CER	c/R	c/r	K	alfa clma	alfa clzer	del alfa	K*Θ/0.136	delay ang
0.050	0.050	1.000	0.178	9.000	-1.200	10.200	1.307	3.135	
0.150	0.157	1.043	0.171	9.000	-1.200	10.200	1.312	3.183	
0.250	0.147	0.589	0.289	9.000	-1.200	10.200	1.250	2.555	
0.350	0.138	0.394	0.418	9.000	-1.200	10.200	1.209	2.131	
0.450	0.129	0.286	0.560	9.000	-1.200	10.200	1.177	1.802	
0.550	0.119	0.217	0.722	9.000	-1.200	10.200	1.150	1.527	
0.650	0.110	0.169	0.907	9.000	-1.200	10.200	1.126	1.285	
0.750	0.100	0.134	1.122	9.000	-1.200	10.200	1.104	1.062	
0.850	0.086	0.102	1.444	9.000	-1.200	10.200	1.079	0.805	
0.950	0.082	0.086	1.681	9.000	-1.200	10.200	1.064	0.653	

The baseline 2D wind-tunnel data set is shown in Fig. 4a for a Reynolds number of 1,000,000. Although a lower Reynolds number airfoil data set is desirable toward the blade root, this was the lowest Reynolds number data set acquired for the airfoil in the Delft wind tunnel. This data set provides good 2D stall characteristics for angles of attack up to 18 deg. The shape of the post-stall c_l distribution out to 18 deg is largely influenced by the forward movement of the upper surface separation point with increasing angles of attack. For simplicity, the stall delay c_l correction is introduced on the linear part of the lift curve slope that corresponds to 0.1, which is typically at an angle of attack of approximately 6 deg. This results in a 0.1 increase in c_l for each degree of stall delay as seen in Fig. 4b. Retaining the same 2D post-stall shape for the 3D post-stall distribution is questionable since it is strongly affected by the forward movement of the separation point on the blade. The forward movement of the separation point for 3D post-stall would likely differ from the 2D case. The significance of this difference needs further study. Beyond 18 deg the airfoil characteristics transition into flat plate theory.

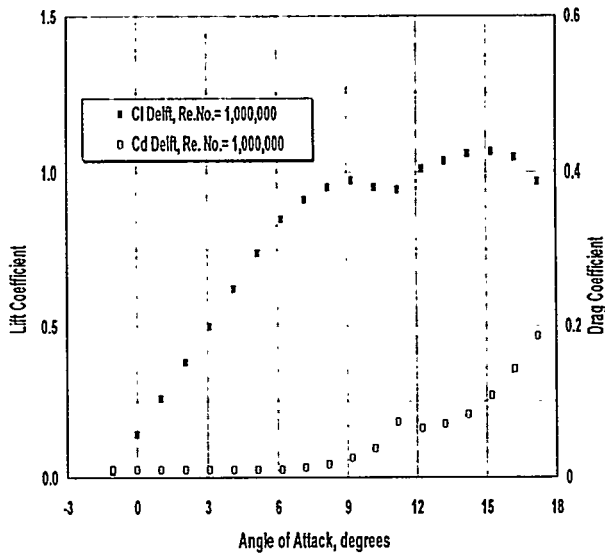


Fig. 4a S809 Delft 2-D wind tunnel data.

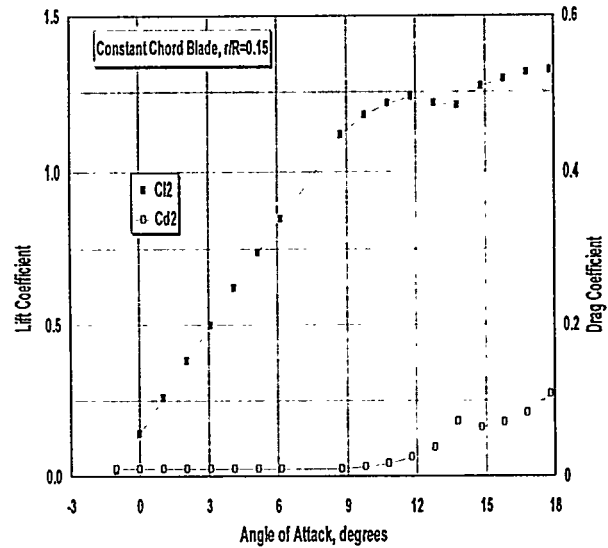


Fig. 4b S809 Delft data with stall delay.

For the constant-chord CER blade, the modified 2D data set, which includes the post-stall 3D lift and drag correction, is shown in Fig. 5a. All blade segment airfoil characteristics were modified to include 3D post-stall effects for the PROP93 performance prediction. For clarity, the airfoil characteristics are shown for only every other blade station. In the root region the post-stall $c_{l,max}$ increased from 1.1 to more than 1.3 as a result of 3 deg of stall delay. This increase in c_l is noticeably less than that observed on the CER for this radial station. Due to the blade's constant chord, which results in high tip region solidity relative to a tapered blade, noticeable stall delay of 0.75 deg is predicted for the tip region. Stall delay is also accompanied by a corresponding angle of attack delay for the exponential drag increase. This correction to the drag may not be appropriate as suggested by Harris.¹² In this regard, additional study is needed. For the tapered-chord blade, the modified 2D data set that includes a post-stall 3D lift and drag correction is shown in Fig. 5b.

For the CER, predicted rotor power was calculated using both 2D wind-tunnel data and modified data to account for 3D stall-delay effects. This was done for the current constant-chord/twisted blades and the hypothetical tapered-chord blade having the same chord at 80% radius, which results in a similar torque weighted equivalent chord. A comparison (Fig. 6a) of the predicted power curves for constant-chord/twisted blades showed a peak power increase of 23% for a 75% radius blade pitch of 11.5 deg toward feather which corresponds to a tip pitch of 8 deg for the test data. Although the constant chord blades have less inboard stall delay than a tapered blade they have more outboard stall delay. Slightly more stall delay in the tip region coupled with a high dynamic pressure helps to compensate for less stall delay inboard with a small dynamic pressure.

For the same peak power, the tapered/twisted blades required a pitch angle of 9 deg. A comparison (Fig. 6b) of the predicted power curves for the tapered/twisted blades showed a peak power increase of 28% which was slightly higher than the increase for the constant-chord/twisted blades. Generally, there was not a large difference in the peak power increase due to 3D stall delay for constant chord versus tapered blades.

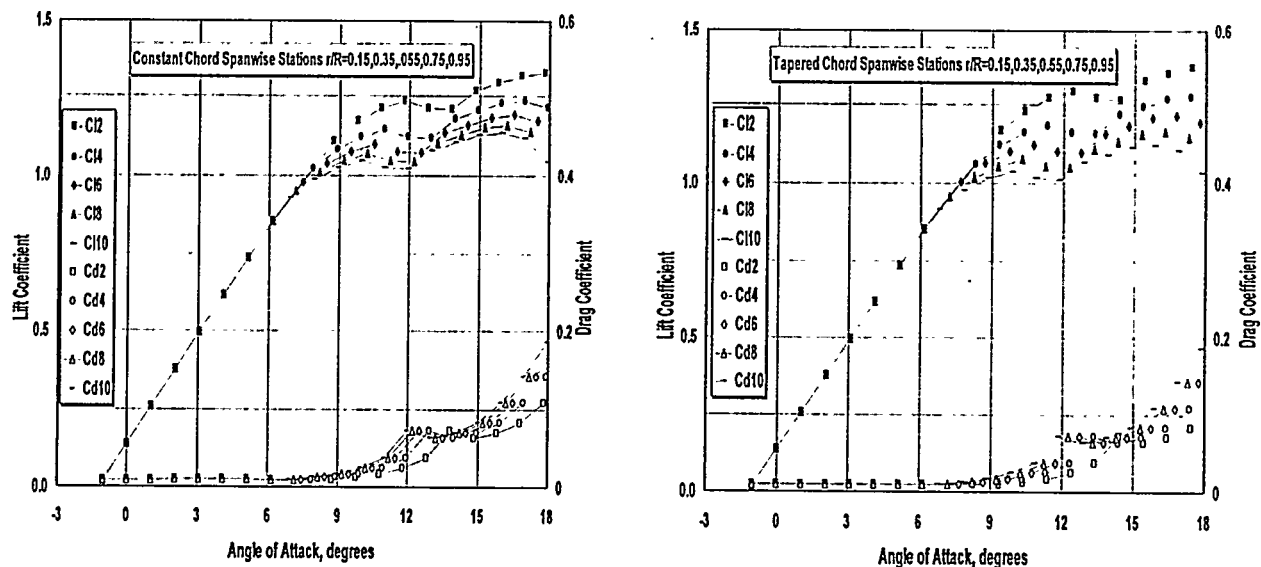


Fig. 5a & 5b Constant-chord and tapered-chord airfoil data sets modified to include post-stall 3D effects.

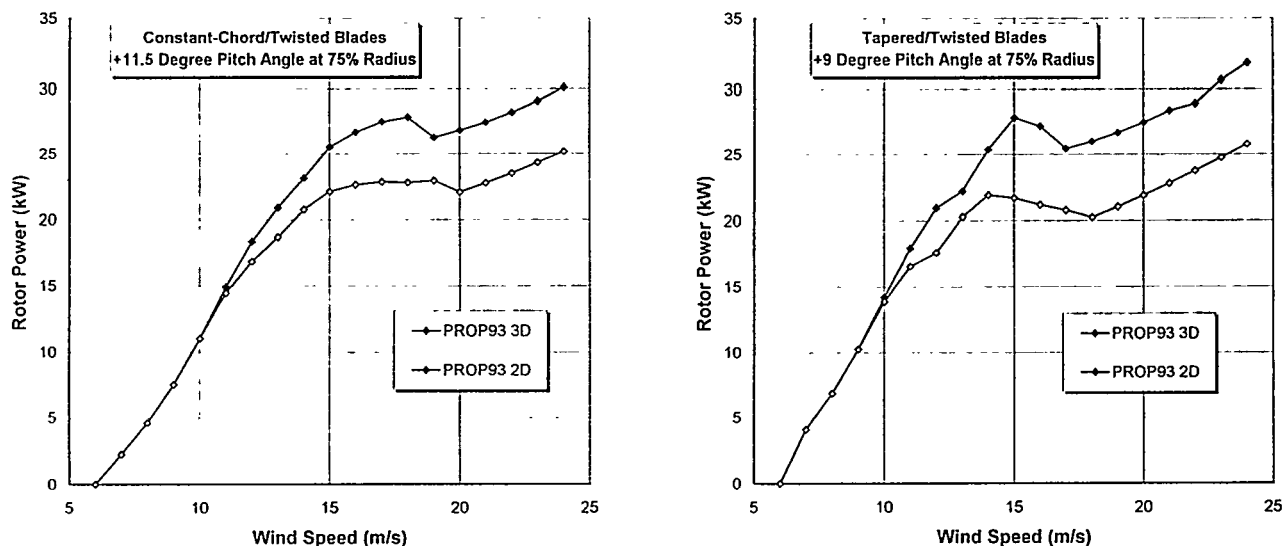


Fig. 6a & 6b Constant-chord and tapered-chord, blade predicted power for 2D and 3D airfoil characteristics.

AWT-26 Rotor

The low solidity AWT-26 blade shown in Fig. 7 was chosen as a representative, commercial blade to further evaluate the stall delay model. Application of the stall delay model to most commercial blades is more complex as a result of different airfoils from root to tip. The AWT-26 blade uses an NREL airfoil family that consists of three different airfoils¹³ from blade root to tip. In the root region, a high $c_{l,max}$ S815 airfoil is used. This airfoil transitions into a thinner, lower $c_{l,max} = 1.0$ S809 airfoil at 75% radius and then to a low $c_{l,max} = 0.9$ S810 airfoil at 95% radius. For these airfoils, reasonably accurate 2D post-stall, wind-tunnel data is needed out to 20 degrees, which is not always available. Airfoil performance characteristics must then be predicted with the Eppler¹⁴ code. With the airfoil's radial location and Reynolds number specified, input data sets can then be prepared using WTPREP.¹⁵ This software package saves the designer much time since it interpolates between the different airfoil characteristics and Reynolds number for each of the spanwise segments as illustrated in Fig. 8a. Using the stall-delay model, the 2D data were modified to reflect 3.5 deg of stall delay in the root region that decreases to zero at the tip as seen in Fig. 8b. This results in a root region $c_{l,max}$ enhancement of 0.35 relative to 2D data. Predicted power using the 2D and modified 3D data sets is shown in Fig. 9. The data set with the 3D stall-delay resulted in a peak power increase of 18% relative to 2D data. Based on previous studies this percentage increase appears to be fairly realistic.

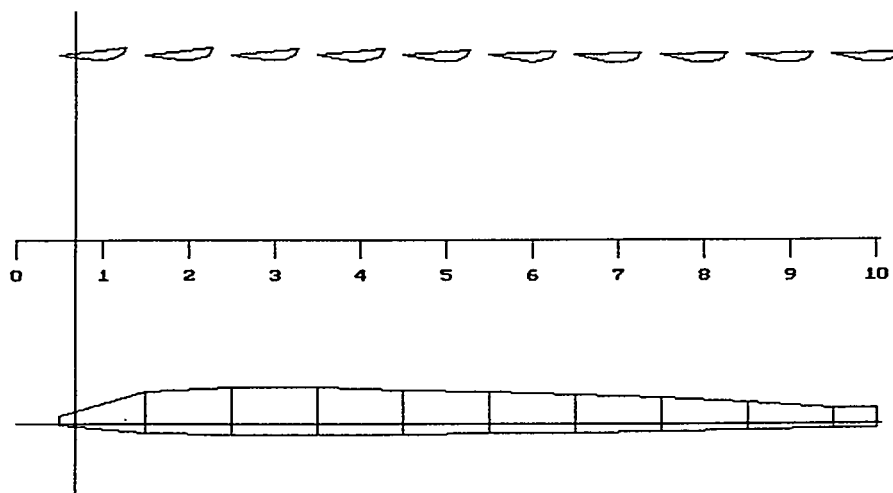


Fig. 7 AWT-26 blade geometry.

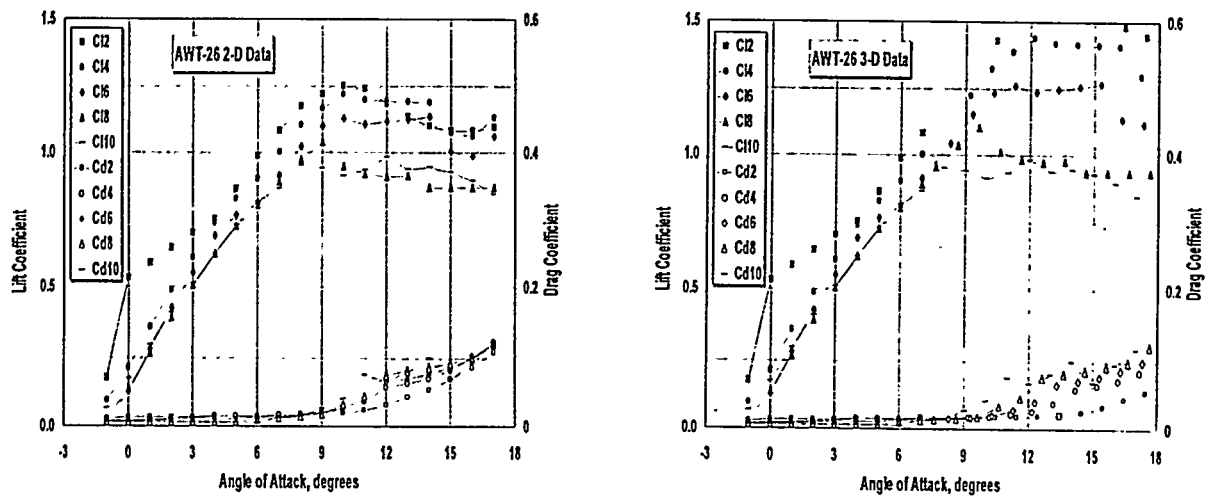


Fig. 8a & 8b S810, S809, and S815 airfoil 2D and 3D performance characteristics.

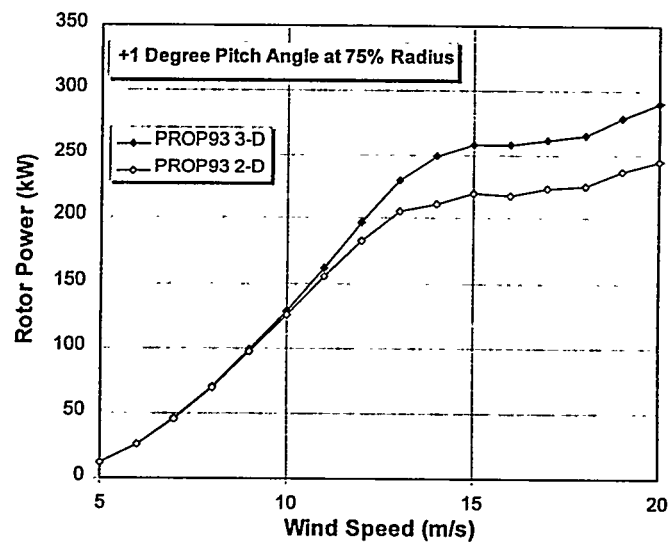


Fig. 9 AWT-26 rotor performance calculated with 2D data and the 3D post-stall model.

Comparisons of Measurements and Predictions

Comparisons between predicted and measured power for the CER and the AWT-26 showed discrepancies that raised questions, which could not be adequately answered. However, these discrepancies should not reflect on the accuracy of the Corrigan and Schillings stall-delay method.

Measured electrical power for the CER was obtained for a blade tip pitch angle of +8.0 deg. Each baseline cycle data point represents the power for one revolution in time. Relatively steady-state conditions were present for each data point where it differed little from adjacent cycles on each side of the data point. The yaw error for the data was limited to ± 5 deg. These data sets were also binned on pitch angle since some elasticity in the control system resulted in a tendency for the pitch to shift about 1 1/2 deg toward feather at high wind speeds. To convert CER predicted rotor power into electrical power required the drive train efficiency curve of Fig. 10.

For the CER, good correlation with test data is shown in Fig. 11 at medium wind speeds. However, predicted peak power using the 3D stall delay correction was significantly higher than measured power while predicted peak power resulting from 2D post-stall characteristics was in closer agreement with test data. Potential error sources for the discrepancy with 3D post-stall calculations can be attributed to both power measurements and the inherent assumption that the shape of the 3D post-stall distribution is the same as the 2D post-stall distribution. It should be noted again, however, that the 3D post-stall model yielded a lower $c_{l,max}$ than experimental data. Another aspect to consider was that one of the three blades of the test rotor was covered with tufts for flow visualization with a radially aligned video camera. Five large pressure probes were also mounted along the blade's leading edge. As a result, this blade had significantly more drag which likely accounts for a good portion of the discrepancy between 3D predicted and measured data. Further work is necessary to investigate these error sources along with the possibility that the empirical stall-delay model itself could be overestimating the lift enhancement.

Measured electrical power for the AWT-26 was obtained at the Tehachapi, California, wind site for a blade tip pitch of 1.0 deg.¹⁶ The power curve was derived from 300 hrs of data using 1 min averages of 1 sec data points. While establishing this power curve, significant variations in turbine efficiency were noted with changes in the season and turbulence intensity. Predicted rotor power was converted into electrical power using the drive train efficiency curve of Fig. 12.

The comparison of predicted and measured power for the AWT-26 is shown in Fig. 13. The use of 2D airfoil data significantly underpredicts peak power. The use of the 3D-stall delay model provides better agreement with measured peak power but still underpredicts peak power by about 10%. Predicted power also includes a slight increase in rpm around peak power of 1.7% to account for generator slip. The discrepancy between predicted and measured power is partly related to lack of an adequate 2D-airfoil database and the omission of aerodynamic modeling of the tip brake plates. Typically, tip plates result in an increased angle of attack and power in the tip region. In addition, alterations of the measured power curve for seasonal and turbulence intensity has not been quantified.

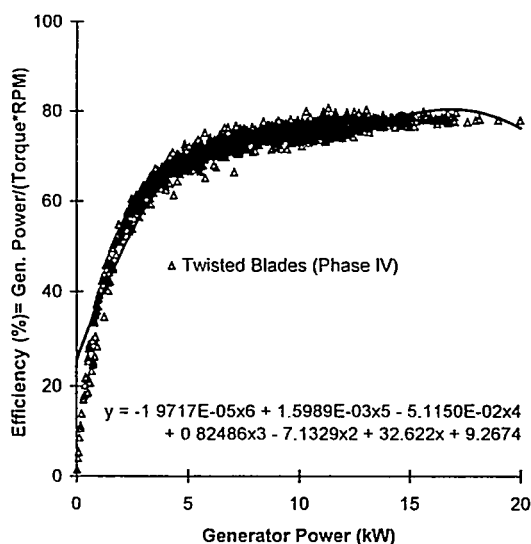


Fig. 10 Drive-train efficiency for the CER.

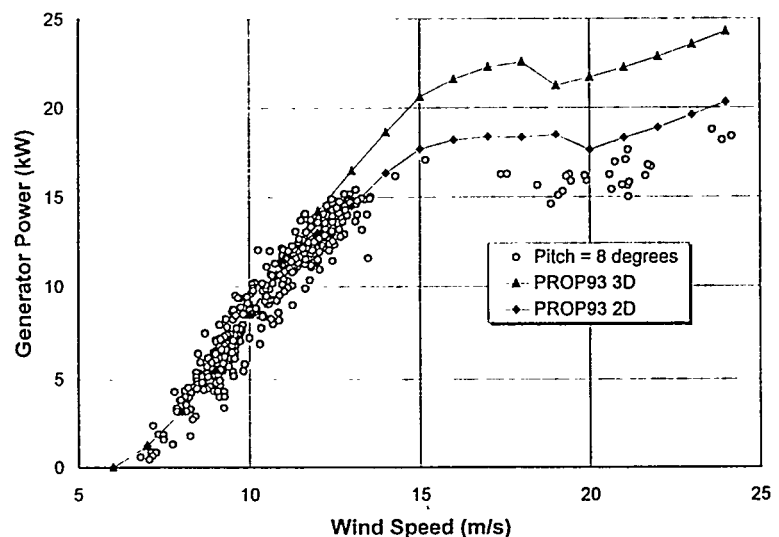


Fig. 11 Comparison of 2D and 3D predicted power curves with measured data for the CER.

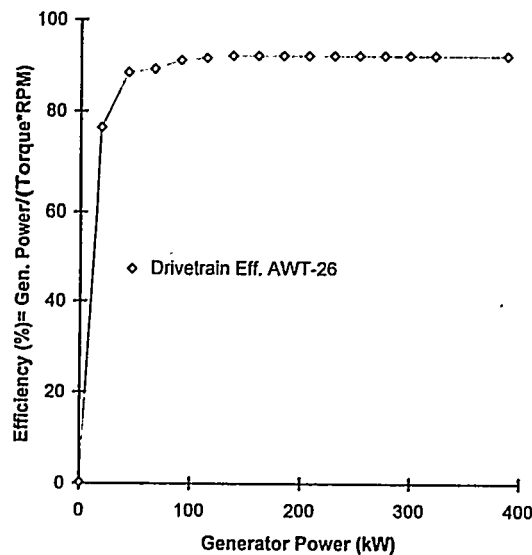


Fig. 12 Drive-train efficiency for the AWT-26.

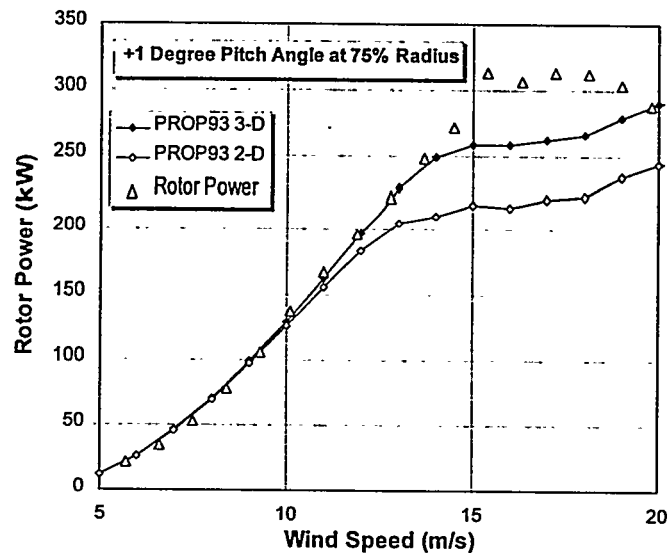


Fig. 13 Comparison of 2D and 3D predicted power curves with measured data for the AWT-26.

CONCLUSIONS

The Corrigan and Schillings empirical model for predicting stall delay due to rotation appears to quantify the first-order effects through the product of a shape factor that is proportional to the local blade solidity and the airfoil's angle of attack range for positive c_l which is proportional to its camber. The method is easy to implement by modifying the 2D airfoil data tables and provides a realistic increase in overall rotor power. The accuracy is dependent on the measured post-stall 2D airfoil characteristics up to large angles of attack of 18 deg and more. The method predicts a smaller increase in the root region c_l than CER data and inherently assumes that the 3D post-stall distribution will be similar to the 2D post-stall data, which is questionable.

Results of this investigation yielded peak power increases due to stall delay for the high solidity CER of 20% to 30% compared with results obtained from 2D data. For lower solidity, commercial rotors like the AWT-26, this increase was calculated to be 15% to 20%. Most of this gain is a result of extending the lift curve to greater values of c_l and up to 25% of the gain results from a wider drag bucket. Rotor power increase due to stall delay appears to be relatively insensitive to blade taper. The amount of stall delay increases for blade-pitch angles toward stall. Accounting for stall delay is most important for stall regulated rotors for accurately predicting peak power. Neglecting this 3D aerodynamic component leads to excessive blade solidity and peak power that has to be overcome by excessive blade pitch toward stall. The importance of including stall delay for variable pitch rotors and variable rpm is mainly for determining the wind speed for regulating peak power.

Recommendations for refining the prediction of stall delay should include the following work. A better understanding is needed of the influence of the blade's spanwise pressure gradient on stall delay. Also needed is an evaluation of the inherent assumption that the shape of the 3D post-stall c_l distribution is the same as that for 2D data. If the assumption is reasonable, the airfoil database for 2D post-stall needs to be extended for many airfoils to higher angles of attack. Correlation of the method with other rotor data sets is needed along with the evaluation of other post-stall models. Empirical constants used in the stall delay method require further evaluation for their reasonableness. Details of simplified empirical post-stall methods could also benefit from further comparisons with CFD predictions.

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A STATUS REPORT ON INTERNATIONAL UTILITY-SCALE WIND ENERGY MARKETS

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EXECUTIVE SUMMARY

AWEA's latest ten-year projections for new installations of utility-scale wind turbines show nearly 30,000 new megawatts (MW) should be installed between the years 1997 and 2006. The study also briefly explores the potential impact of a significant event, such as a fossil fuel price spike or a strong move to slow global climate change, that could double installed new wind capacity to nearly 60,000 MW over the same period.

This outlook is substantially more optimistic than last year's (about 20,000 MW), but the numbers are somewhat skewed by rolling the outlook forward one year. In other words, the new projections cover a ten-year period beginning one year later than last year's study. The skewing is a result of substituting the lowest year in last year's study (1996) with the highest year in the new ten-year period (2006), when far more capacity additions can be expected. In addition, AWEA has adjusted upward the numbers for some countries, most notably Germany, Denmark, Spain, Italy, China and the US. Last year's projections were decidedly, and purposefully, conservative but trends are such that greater optimism about future markets (1998 and beyond) is justified.

The wind energy industry installed 1273 MW in 1996, crossing the 1200 MW threshold for the second year in a row. Total worldwide wind capacity at the end of 1996 stood at 6259 MW, with 1996 additions representing a growth rate of 25% over the total installed capacity at the end of 1995. The previous year, 1995, established a record annual high in capacity additions of 1286 MW. For 1996, AWEA had predicted a slight slowdown from 1995's torrid pace primarily because of political conditions in several of the largest markets, a projection which proved to be quite accurate (1271 MW projected vs. 1273 MW actual). AWEA expects 1997 installed capacity to continue on a pace similar to 1996, or approximately 1260 MW, despite a significant slowdown in India. AWEA expects substantial growth to occur in 1998, when AWEA projects 1715 new MW to be installed.

STUDY DESIGN AND PURPOSE

This report is designed to provide US industry, government agencies and others with an ongoing accounting of actual and planned¹ wind technology installations in international markets for utility-scale wind energy technology. The primary objective is to have sufficient data to do market projections based on an accurate count of total existing installations, new installations on a calendar year basis and planned capacity additions worldwide. While all data collection was carried out with appropriate

¹ Planned projects may include formal or informal goals depending on how credible are such goals.

confidentiality safeguards to ensure companies would be willing to provide current and accurate information, few companies were willing to report on projects that are currently under negotiation or have not been publicly announced. This reluctance has led to an underestimation in the database of the total number of planned or potential projects. AWEA utilized both public and privately held information to make year-by-year projections of installed megawatts (MW) for the ten-year period from 1997 through the year 2006. AWEA plans to update these projections on an annual basis at the beginning of each year, assuming that this task continues to receive sufficient financial support from the funder of this activity, the US Department of Energy. This report focuses on markets for utility-scale wind technology. Small-scale wind technology markets are not addressed here.²

ASSUMPTIONS: Base Case and Optimistic Scenario

Base Case

This study focuses on a "base case" that assumes no significant political shifts that would cause a major jump or drop in the various national support schemes for wind energy. The projections also assume only minimal shifts in fossil fuel prices or efficiency gains from combustion technologies. Fossil fuel prices are assumed to be as likely to go down slightly through the year 2006 as to go up slightly. This is a very conservative assumption, given that a price shock of any significant size would shift the projections of wind capacity up considerably, since wind technology represents a hedge against fuel price increases. It also assumes only moderate improvements in the cost of wind and generated electricity, which would mean a leveling off of recent trends that have seen costs drop more rapidly than expected. What gains wind technology is likely to make over the next 10 years may be partially offset by conventional technology efficiency gains. Continued rapid progress on wind technology cost reductions would also accelerate growth considerably. Another factor that could cause much more rapid growth would be an environmental "hammer" of sorts such as enforceable caps on greenhouse gas emissions and/or tradable emissions credits.

Optimistic Scenario

In the 1997 version of this study, the authors have for the first time looked at a plausible "optimistic" scenario to see what the potential range might be for total newly installed capacity by the year 2006. The scenario selected assumes an event, or series of events, linked either to climate change or fuel price spikes, that significantly raises the demand for wind technology. It is assumed that the earliest such events would happen would be the year 2000, while it would be at least the following year (2001) before any significant change in installed capacity would be observed. The assumed annual increase in installations is 33% which, while perhaps conservative for an optimistic scenario, takes into account potential constraints such as production capacity, financing availability for wind projects, knowledge and acceptance of wind technology by utilities and other purchasers of power or equipment. Under

² "Wind farm" markets are defined as those markets utilizing utility-scale turbines, typically at least 50 kilowatts (kW) with most individual turbines being installed currently averaging over 300 kW.

this scenario, the total installed capacity in the years 1997-2006 would double to just nearly 60,000 MW. These optimistic numbers are not reflected on the attached spreadsheet, and reference to this scenario can only be found on the attached graphs.

METHODOLOGY

This study does not purport to be a highly rigorous or quantitative analysis of world markets for wind technology. The authors have utilized primarily qualitative methods to make a reasonable estimate of the likely trends for utility-scale wind installations worldwide. As a foundation, AWEA has collected a great deal of data on existing projects, particularly on the most recent years from 1994 to 1996. Note that some countries collect data on a basis other than the calendar year (i.e., fiscal years such as in India), so some differences may be found in the accounting. Other differences in accounting for capacity may be due to the fact that "installations may not be defined in the same way (i.e., erected vs. operating vs. commissioned, etc). From this base, AWEA has made both quantitative (trend lines) and qualitative judgments about the likely direction, location and pace of future wind activity. Qualitative judgments were based on literature reviews, interviews with knowledgeable industry observers and participants, and the knowledge of ongoing activities collected by AWEA staff in the normal course of carrying out its programs to promote wind technology in the US and overseas. As noted above, AWEA has utilized both public and privately held information to make its year-by-year projections of installed megawatts (MW) for the ten-year period from 1997 through the year 2006. Some projections are based on formal or informal goals as set by various countries but, wherever feasible, AWEA applies a "credibility" test to all goals so that overly optimistic or purely political goals do not bias the projections upward. A "credibility" test consists primarily of reviewing past and current activity to see whether past pronouncements have been realized, particularly to evaluate the "political will" present in a given market, as well as talking to industry observers who are in a position to evaluate the achievability of such goals. AWEA also tries to identify significant potential constraints or accelerating factors that may not be sufficiently considered and corrects the trend lines accordingly. Please note that actual installations year-to-year for any given country may vary significantly from the projections contained herein. This study focuses on trendlines and total installed capacity over a number of years.

MARKET SUMMARIES

Germany and India Lead the World Again

Germany and India once again were the largest markets, accounting for 55% of total worldwide additions in 1996, even though India was down substantially from its rapid growth in 1995. Germany surprised many, including AWEA, who thought that there may be a significant slowdown of new capacity due to challenges to the country's Electricity Feed Law, which mandates payments to wind projects at a rate equivalent to 90% of the average retail power rate. However, Germany installed 438 MW, the second highest total ever for any single country, second only to the 498 MW Germany installed in 1995. Germany will certainly pass the United States in total installed capacity in 1997, the only uncertainty being a determination of actual US installed capacity taking into account decommissioned projects. India saw only 264 MW installed versus 383 MW in 1995. The primary reasons were political, related to the countrywide elections that dominated India's attention for several months.

Predicted Broadening of Markets Begins to Show

In 1996, AWEA had projected a broadening of the markets for wind energy that showed decreasing reliance on Germany and India, which accounted for 66% of 1995 wind capacity installations. Germany and India accounted for only 55% of 1996 worldwide installations, illustrating the projected trend downward, and the projections for 1997 show as little as 41% coming from Germany and India. The primary reason is the slowdown in India, while Germany should continue to account for nearly one-third of all wind installations by itself in 1997. By the year 2000, Germany may account for as little as 15% of new annual installations, assuming that country maintains its current level of installations, while Germany and India together might account for less than 30% of new additions. Such a broadening of markets for wind energy makes the industry less vulnerable to political changes in any given country and is likely to help build a more stable industry.

Nearly 30,000 New MW Projected 1997-2006

This study anticipates nearly 30,000 new MW to be installed over the next 10 years, representing a market of approximately \$30 billion. Western Europe should continue to dominate the world markets in new installations, barring significant political changes that would threaten the generous wind market support structures that are now in place. The Americas as a whole should not be far behind as the US market recovers in 1998 and then expands rapidly after the year 2000. The Asian market should continue to expand rapidly but is highly dependent on India, which is driven by tax incentives and uncertain politics, and the People's Republic of China, whose wind market may be constrained by its difficulty in providing a stable, acceptable investment and trade environment.

Salient results of this study are the following:

- projections for new wind installations from 1997 through the year
2000: 7,840 MW
2006: 29,725 MW
- regional projections for new wind installations by 2006:
 - . Western and Northern Europe: 14,310 MW
 - . Americas (North and South): 6,950 MW
 - . Asia: 5,970 MW
 - . Other: 2,495 MW
- by the year 2006, as many as 38 countries would have at least 50 MW installed, representing 28 new countries compared to today.

Germany and India Once Again Lead the World in Installations

The best markets for wind technology in 1996 (India and Germany together accounted for 55% of worldwide installations) were driven by highly favorable power prices (Germany) or heavy tax incentives (India). The support structures in both of these markets are under pressure, and some changes are likely in the near term, at least in India.

AWEA expected India to increase its wind capacity by another 400 MW in 1996 and was well on its way to doing so early in the year. By the end of the first quarter of '96, the country had installed almost 200 MW of wind energy. However, the remainder of the year brought a total of only 64 MW (for a total of 264 MW) primarily because of uncertainty centered around the elections, leaving India's total capacity at 829 MW. Nonetheless, India was still one of the two major markets for wind energy in 1996 and surpassed Denmark to rank third in total installed capacity after the US and Germany. India is likely to rank second again in 1997 capacity additions even with a much slower market but could be passed by Denmark if that market exceeds expectations again.

The main reason India will be slow in 1997 is a change in the corporate tax rate (from 43% to 35%) that reduces the tax shield provided by the 100% depreciation in the first year by about 18%. In addition, the government is reported to be planning to reduce the first year depreciation to 50% of the capital cost of the turbine. These fiscal considerations have combined with the very tight credit conditions and lower corporate profitability of late to slow all business investment. A further brake on development in India this year may be provided by the poor production experienced by most of the installed turbines. Most turbines in India were developed with European regimes in mind (95% are of European origin or design) and thus have rotors that are undersized for the low wind conditions prevalent in India. Extremely low capacity factors, resulting from hanging relatively small rotors on large nameplate capacity generators, are creating some concern among investors and dampening the enthusiasm that was present in 1995 and early 1996. There is strong interest in moving toward a production type tax credit sometime in 1997 or, more likely, 1998. This move would not only revitalize installations but would provide the kind of long-term incentive for high production that is now missing.

The German market continues to perk along despite substantial opposition to the Electricity Feed Law (EFL) from utilities and a conservative faction in the government, as well as increasing difficulty in siting new projects. AWEA expected a substantial slowdown in the German market which did not materialize in 1996 and is not likely to in 1997 either, as it appears that no major changes to the EFL are imminent primarily because of the popularity of wind energy with many German voters. With an election looming in 1998, few conservatives will want to take on environmentally friendly wind energy.

The next significant challenge to the German wind market may come from competition in the German electric sector, which is likely to lower the average retail rate upon which the EFL is based, but this impact is probably a couple of years off, if not more. A second, and perhaps more important, impact from competition is the pressure on the part of utilities to move the burden of the EFL off of German utilities, which will now have to compete in the broader European market, and onto consumers. The EFL will become a target again, but election results will help to determine how strong a position the wind industry will have. Some changes are thus likely to be made to appease the utilities, but compensating changes not directly affecting the utilities are also likely. While it is likely that the overall result will be lower prices for wind projects, this result will not be the disaster that German wind advocates are foretelling. AWEA's projections for Germany average 400 MW per year for the next ten years, which may seem like a high number, but this would still be below the average level of the last two years.

Other European Markets

Western Europe will continue to be the site of most new installations worldwide for the next decade. It was expected that growth in Denmark would be somewhat slow since there was an uncertainty of government and utility support. Surprisingly, despite this uncertainty, Denmark installed 190 MW of new capacity in 1996. The Netherlands, however, only added 60 MW which was in line with previous predictions. The UK installed only 71 MW in 1996, contrary to expectations that it would bring more generation on-line from one of its previous NFFO rounds. Much of this new generation should come on-line in 1997, and therefore, the UK should see much more growth. However, after these obligations are fulfilled, there is quite a bit of uncertainty about the future of incentives (or at least a fair playing field) for wind projects under deregulation.

Some public opposition on the issue of siting wind turbines is springing up in the more densely populated countries of Europe, but this is unlikely to cause a major overall drop in expected installations. Spain, Italy and Greece are the three new markets that are seen as potentially strong growth areas, with Spain having the largest potential of the three and being much further ahead in development. Spain managed to install at least 90 MW in 1996, although this level was considered a disappointment, and should install even more in 1997 and beyond. Italy installed nearly 50 MW in 1996, with the promise of at least that much in 1997. There is some concern about challenges to the existing wind incentive program in Italy, which throws a great deal of uncertainty into the mix there, but announcements of projects continue to be made. Greece saw virtually no growth in installed capacity, last year, due to delays in obtaining contracts with the Public Power Corporation for buying wind generated electricity. However, these problems are slowly being resolved, and some construction

could begin in 1997 with most falling into 1998 and beyond. France has recently announced its intentions to join the wind race, although it will take several years to get significant projects in place. Sweden is also showing some signs of real growth after many years of good intentions but little action (38 MW installed in 1996).

The Americas

The US market will continue to stagnate in 1997 as restructuring sweeps across the country. The primary driver for projects from 1997 to 1999 is the expiration of the production tax credit at the end of 1999. Entry of new projects that would come on after 1999 will slow dramatically but a minimum level of project development is likely to continue as a result of various state mandates to build clean energy projects, a scenario under which wind will capture a significant share. Adoption of a version of AWEA's portfolio standard proposal (requiring all generators to include a percentage of renewables in their portfolio and making that percentage a tradable commodity such as with emissions credits) would put the wind industry back on track, but it is much too early in the process to predict outcomes and relief would not likely come until at least 1998 and probably later.

There has been substantial confusion as to what is the actual count of installed capacity in the US. It has been difficult to collect data on privately held turbines, and adding to the confusion has been notice from the utilities that they "found" 70 additional MW that were unaccounted for in previous assessments. This addition more than counterbalanced the 60 MW that were decommissioned in 1996.

Other turbines are in a gray area, meaning that they may be capable of operating but may or may not be run on any given day depending on the winds and the payments per kWh they receive. These turbines may appear to be out of service but technically are not, although it is difficult to differentiate them from those turbines that are not operating at all. The number AWEA has used, 1794 MW, is a best estimate arrived at by the US Department of Energy with the assistance of AWEA, the Kern Wind Energy Association and the California Energy Commission. Additional capacity may have been decommissioned in 1997 but these turbines are not reported in this year's study.

Canada is still very uncertain, since plans to mandate federal "green power" purchases have not materialized yet, and other projects are moving forward but slowly. Ambitious project proposals in Alberta, Quebec and Ontario will be important tests of how fast wind development will move in Canada. If one of them breaks through, Canada as a whole could become a significant player on the international wind scene fairly quickly. A long-awaited but potentially strong market for very small wind farm projects to supplement remote diesel power systems is expected to develop in Canada within the next several years but not in 1997.

Encouraging signs for development outside of the US and Canada have been shown in Mexico, Costa Rica and Brazil. Mexico's energy ministry now has mention of its long-awaited wind solicitation on its world wide web page. The project had been expected to be announced at 27 MW but was bumped up to 54 MW because of the enthusiastic response of the national utility's top officials. Several other 20-30 MW private projects are also being pushed but private power regulations are not yet adequate to allow them to be built. Already one of the three approved 20 MW Costa Rican projects has been built

and is operating. The additional projects are still being developed but construction will probably not begin until 1998. The national utility would reportedly like to have a little more operating experience with their first project before others are connected. Other projects are moving forward in Central America totaling 50-75 MW but information regarding them is confidential. Several large projects in Brazil are being eagerly pushed by utilities in the states of Ceara, Parana and Minas Gerais. These projects are not moving as quickly as had been hoped but some construction may begin in 1998.

Projects in Argentina are moving slowly or have even suffered setbacks because of unfavorable treatment of wind projects under the new private power regime. The price of power from the grid continues to drop, which makes the economics of wind projects difficult at best. In addition, wind projects would at present receive no capacity payments and may even be subject to a penalty for reactive power unless changes are made by the government. Nonetheless, there is still strong interest in Argentina in exploiting the country's huge wind resource, and some action to encourage such development is likely but may not be very timely.

Asia

As described earlier, India should continue to be one of the top two markets in 1997 despite the tax changes described earlier. With the tight credit market and slowing economic conditions, it is difficult to see that market taking off again until some changes are made in the tax code for a production-type credit and corporate profits improve. Still, there is a strong government commitment to pursue wind energy and a strong recovery is quite likely but probably not until 1998. Sri Lanka is beginning to show a similar, if smaller, interest in wind development in comparison to its giant neighbor, and some small demonstration projections are all but assured. Larger scale development is certainly a possibility but the total market in Sri Lanka is relatively small. Pakistan has also shown strong interest for a number of years, and has a number of good sites, but little has come of it despite periodic flurries of activity.

China has positioned itself for major expansion if the country can deliver on its intent to accelerate wind development, but this is a big question. As much as 100 MW is predicted to go on line for 1997, although 75 MW is perhaps more likely. In 1996, the country nearly doubled its wind capacity from 36 MW to almost 60 MW. Nevertheless, these figures indicate that China will still fall short of its goal of installing 1000 MW of wind energy by 2000. China will still rely heavily on tied aid to build initial projects, but commercial (non-aid funded) projects are beginning to make their way into this market. China, although it is moving in the right direction, still has several barriers it must deal with before wind energy can experience explosive growth. First, it is still very difficult to do business in China (foreign exchange availability, contract sanctity, proprietary technology protection, bureaucracy, etc.). Second is the plethora of inevitable trade and political disputes between China and the rest of the world as it lumbers onto the world economic stage, and reabsorbs Hong Kong in mid-1997. One of the key questions regarding China is how much of that market will be open to foreign vendors, since the Chinese are keenly interested in developing their own industry. Heavy reliance on locally produced turbines, reflecting China's strong penchant for tight government control of market development, reinforced by punitive import tariffs, could delay the growth of that market by several

years. These issues will frustrate, although not necessarily stop, many developers and vendors who haven't made a long-term commitment.

On the optimistic side, China has the capability and demand to become one of the top two or three markets, or even the largest market in the world, by the year 2006. China therefore represents the largest source of uncertainty in this study, although the error it represents is much more likely to be on the high side (far higher numbers than AWEA has projected) than on the low side. This bias toward the high side provides much greater confidence that the numbers projected in this study can be achieved.

Australia and New Zealand are certainly good potential markets, with New Zealand well out in front in terms of the development process but Australia representing a larger potential (New Zealanders, with a much stronger inclination toward wind energy, may not agree). With strong wind resources and healthy economies, these markets should be good prospects, but with populations of 3 million and 15 million respectively, they pale in comparison to the potential in many other more densely populated Asian countries. The Philippines, for instance, has nearly four times the population of New Zealand and Australia combined and has far higher electricity demand growth, albeit starting at a far lower per capita rate. On the other hand, New Zealand and Australia are several years ahead of the Philippines in terms of wind development and are likely to see far more installed capacity in the near term.

The Philippines continues to show strong interest in wind, although there is a widespread belief that typhoons make wind technology a non-starter, a proposition that no one seems to have any data to back up. A windmapping effort just getting underway will look at the issue of the probability of typhoons at any given location and should provide a more formal rebut to this common refrain. In addition, there are turbines on the market that can either survive all but the strongest (and most infrequent) typhoons or can be tilted down during peak wind periods. Resources are clearly very good in the north, while the south probably has limited areas with sufficient wind for wind farms. Whether all this interest will generate development of small to medium-sized wind farms is uncertain at this point, but all the ingredients are present. A strong effort has been mounted by the government to utilize renewable technologies, particularly wind, for remote generation, and strong interest has also been shown by the private sector.

Indonesia, Vietnam and even Thailand are beginning to receive some attention in regard to utility-scale wind projects, but all that is clear is that each will offer good opportunities for small systems within the next several years. Some wind farm quality sites have been tentatively identified in Indonesia, while Thailand's winds look marginal to just adequate in preliminary studies. Little is known about Vietnam's wind regime, but it should be reasonably strong at least on the coast. Wind farm markets in these countries are unlikely to be realizable before the year 2000, with the possible exception of a demonstration project or two.

CONCLUSIONS AND PROSPECTS FOR THE US WIND INDUSTRY

The picture for wind technology globally is even more encouraging in this year's projections than in last year's version. Europe will far outpace all other regions for the foreseeable future, especially if Spain, Italy, and France develop as expected. The US market looks more promising at this point than it did last year, but the numbers won't show a strong recovery until 1998. The US industry is now dominated by one player, Zond Corporation and its major backer Enron, with several smaller companies seeking to maintain and expand their place in the market by focusing on international markets and a few smaller domestic projects. Zond has recently signed the two largest wind contracts ever let in the last year (107.5 MW and 112.5 MW, respectively), but these are projects on US soil. US companies, particularly the smaller firms, will continue to be pressured by the variety of non-US wind companies, old and new, competing in the wind business internationally with their home governments behind them with subsidies and tied aid. The Spanish industry is just beginning to make its presence felt, and new companies from other parts of Europe continue to spring up. This intense competition should keep equipment prices down and profits margins relatively thin, except those that are able to find a market niche with lower levels of competition.

Tied aid will continue to be the name of the game outside of Europe in 1997, and US firms will once again be challenged by this environment, since Europe's governments actively support their wind industries overseas with significant tied aid programs. US firms are also relative newcomers to many international markets and are in a catch-up mode in comparison to their European counterparts. In addition, European governments have proven much more willing to provide strong domestic market support that benefits their country's firms. A vibrant and stable domestic market has proven to be a successful foundation for the development of a strong wind industry in many European countries. On the other hand, the US market has varied tremendously depending on the prevailing political environment, which creates a very difficult business environment for US firms. The bankruptcy in 1996 of the largest US wind firm, Kenetech Windpower, is testament to the volatile nature of the US wind market. Although Kenetech had many problems to solve, the sudden collapse of the US wind market in the wake of restructuring was certainly the killing blow for that firm. The market share that US firms will be able to capture in the future is thus highly dependent on how US government policy evolves over the next several years, since strong home market support and tied aid for the benefit of foreign competitors currently tilts the playing field in favor of non-US firms. US market share thus may not see much improvement from the level of less than 10% in 1997 until calendar year 1998 when many US projects in the pipeline will begin to go on-line both in the US and overseas.

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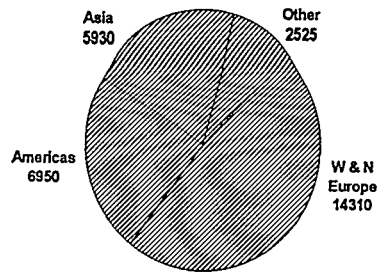
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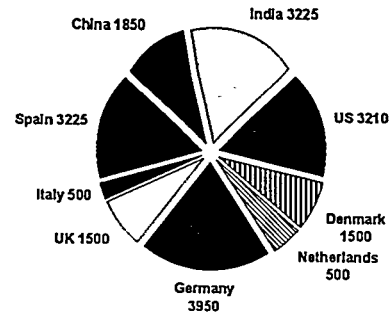
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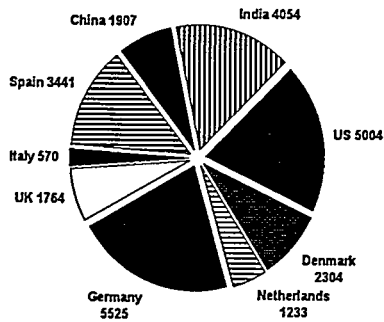
New Windpower Additions By Region
1997-2006 (MW)



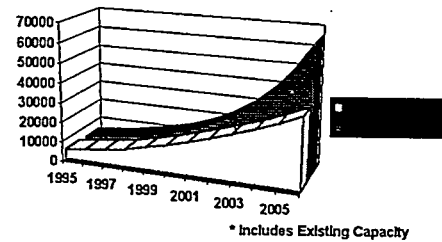
Total Newly Installed Wind Capacity
By Country 1997-2006 (MW)



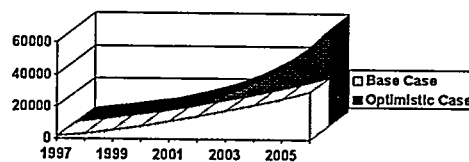
Total Installed Wind Capacity
By Country 1997-2006 (MW)



AWEA Projections of Total Worldwide
Wind Capacity (MW) 1997-2006*



AWEA Projections of
Worldwide New Wind Capacity
1997-2006 (MW)



BASE CASE	1994 1994 Year End	1995 1995 Year End	1996 1996 Year End	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006 Total	Total Capacity *
	New Capacity	New Capacity	New Capacity										New Capacity	
United States *	41	42	42	1770	1784	1790	1790	1790	1790	1790	1790	1790	1790	1790
Canada	18	23	21	21	21	21	21	21	21	21	21	21	21	21
Denmark	52	54	54	54	54	54	54	54	54	54	54	54	54	54
Netherlands	21	163	102	102	102	102	102	102	102	102	102	102	102	102
Germany	290	498	498	1137	1576	1576	1576	1576	1576	1576	1576	1576	1576	1576
United Kingdom	32	147	46	93	261	261	261	261	261	261	261	261	261	261
Italy	1	23	1	23	28	28	28	28	28	28	28	28	28	28
Greece	1	28	0	28	28	28	28	28	28	28	28	28	28	28
Spain	8	72	73	128	128	128	128	128	128	128	128	128	128	128
Portugal	0	6	0	6	11	11	11	11	11	11	11	11	11	11
Ireland	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sweden	5	38	29	67	105	105	105	105	105	105	105	105	105	105
France	0	3	0	3	3	3	3	3	3	3	3	3	3	3
Other Europe	5	26	3	29	28	28	28	28	28	28	28	28	28	28
East. & Cent. Europe	4	6	1	7	7	7	7	7	7	7	7	7	7	7
Russia & Other NIS	N.A.	2	1	1	1	1	1	1	1	1	1	1	1	1
Mexico	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Brazil	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Argentina	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Chile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Peru	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other S. America	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Costa Rica	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Honduras	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guatemala	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other C. America	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Caribbean	3	0	0	0	0	0	0	0	0	0	0	0	0	0
China	18	30	7	38	57	57	57	57	57	57	57	57	57	57
India	100	182	383	565	829	829	829	829	829	829	829	829	829	829
Philippines	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Japan	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Asia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Zealand	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Australia	5	14	5	14	14	14	14	14	14	14	14	14	14	14
N. Africa	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Africa	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Middle East	0	24	5	24	24	24	24	24	24	24	24	24	24	24
Turkey	0	10	10	10	10	10	10	10	10	10	10	10	10	10
Others	N.A.	10	10	10	10	10	10	10	10	10	10	10	10	10
TOTAL	619	1286	4968	6259	1273	1715	2345	2520	2840	3285	3425	4020	4520	35984
Key Regional Totals:														
Western & Northern Europe														
Asia (incl. N.H. & South)														
Asia (incl. N.H. & Australia)														
Other														
TOTAL														
Units: Megawatts (MW) of installed nameplate capacity.														
* US number's subject to change because of uncertainty around decommissioning of older turbines. California utilities have changed their accounting for wind capacity and now report approximately 80 additional megawatts.														
NOTE: Some numbers may not appear to add up when adding new capacity to the previous year's total and comparing to the next year's total. This is due mainly to rounding errors and uncertainty about wind capacity removed during any given year.														
NOTE: Numbers are rounded up to nearest MW. Countries with less than .50 MW (one-half MW) are listed at 0 (zero).														
N.A. Not available or unknown.														
NOTE: Spreadsheet for Optimistic Scenario not included.														
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THE INTERNATIONAL ENERGY AGENCY'S ROLE IN WORLD-WIDE WIND ENERGY DEVELOPMENT

Presented at the Annual Conference of the
American Wind Energy Association, June 1997

by

International Energy Agency
Implementing Agreement on Wind Turbine Systems
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ABSTRACT

Wind energy is now being deployed world-wide at a rapidly increasing rate and the International Energy Agency (IEA) has a changing role in its growth. IEA was founded in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to collaborate on comprehensive international energy programs. IEA membership consists of eighteen parties from sixteen countries and the European Commission. Recently there has been increasing interest in IEA participation from both OECD and non-OECD countries. Non-OECD countries participating in various IEA Agreements include: China, India, Israel, Korea, and Russia. Because of its diverse international makeup, the IEA is viewed as a source of reliable technical and economic information. The World Bank has approached the Executive Committee for Wind Energy R & D, through the IEA Renewable Energy Working Party, to assist in the expansion of wind deployment. In addition, IEA is moving from R & D programs to include tracking of implementation incentives offered by its members.

The IEA Wind Agreement is currently working on four tasks, called Annexes, and one additional Annex is planned. Annex XI, titled "Base Technology Information Exchange" involves: (1) the undertaking of joint research in areas where a periodic multi-nation exchange is considered useful; (2) the organization of topical expert meetings on topics such as lightning protection and noise; and (3) the preparation of documents within the series "Recommended Practices for Wind Turbine Testing and Evaluation". Annex XIV, titled "Rotor Aerodynamics", will use coordinated measurements of blade force and pressure distributions on different operating wind turbines to verify aerodynamic models and design codes and to develop improved methods for the design of stall-controlled turbines. Annex XV, titled "Annual Review of Progress in the Implementation of Wind Energy by the Member Countries of the IEA", will produce a review on the progress of commercial wind power development to identify major trends, initiatives, and attitudes which are likely to be of interest to decision makers. Annex XVI, titled "Wind Turbine Round Robin Test Program" is a task initiated in 1995 to validate and improve wind turbine testing procedures through a series of round-robin comparison tests at participating national test stations in Europe and North America. In addition, a new task (Annex XVII) is planned to compile a database on wind characteristics of typical sites within the member countries. Time

series data will be collected on wind resources in a wide range of terrain and atmospheric conditions for use in turbine design.

The future role of the IEA Wind Agreement will address: continuation of collaborative R&D, efforts to assist non-member countries outside the parent Organization for Economic Cooperation and Development (OECD), and transfer of information to other international agencies.

BACKGROUND

The IEA was established in 1974 within the framework of the OECD. The IEA mandate is to foster international cooperation among national programs of research and development of energy technologies. The structure of the IEA is illustrated in Figure 1.

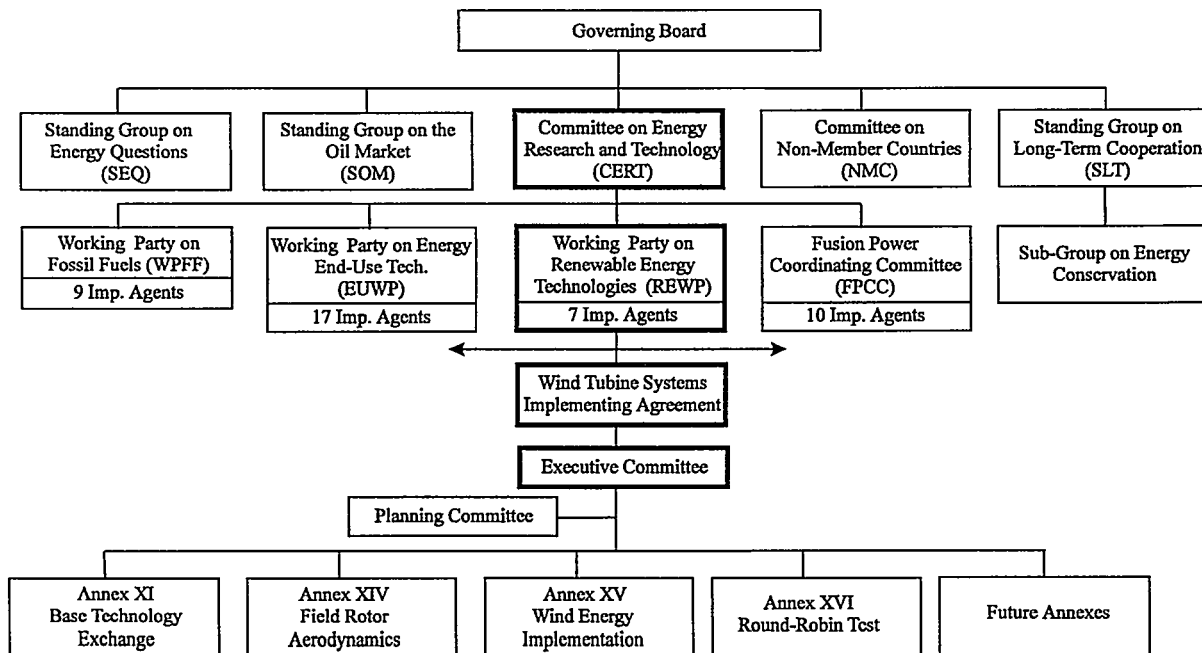


FIGURE 1: INTERNATIONAL ENERGY AGENCY STRUCTURE

Under the Committee on Energy Research and Technology (CERT), the Working Party on Renewable Energy Technologies (REWP) co-ordinates activities relating to all forms of renewable energy. Collaborations in specific fields of renewable energy are undertaken within seven R & D Implementing Agreements, as shown in Table 1. One Implementing Agreement is for Co-operation in the Research and Development of Wind Turbine Systems. "IEA Wind" (for short) concerns all aspects of wind energy from resource assessment to technology deployment. IEA Wind was initiated in 1977, by nine OECD member nations. Its activities are guided by an Executive Committee (Ex Co) of national representatives, usually from government organisations, national laboratories, or electric utilities designated by the National Government.

TABLE 1: PARTICIPATION IN RENEWABLE ENERGY TECHNOLOGY IMPLEMENTING AGREEMENTS (as of 1996)

	Bio-energy	Hydrogen	Hydro-power Technologies	Photo-voltaic Power Systems	Solar Heating and Cooling	Solar PACES	Wind Turbine Systems	Total Participants By Country
Australia					P	P	P (94)	3
Austria	P			P (93)	P		P	4
Brazil							P#	1
Belgium	P	WD (94)			P			2
Canada	P	P	P (95)	P (93)	P		P	6
China			P (95)	P (94)				2
Denmark	P			P (93)	P		P	4
Finland	P			P (92)	P		P (93)	4
France	P (93)		P (95)	P (93)	P			4
Germany		P		P (93)	P	P	P	5
Greece							P (95)	1
Ireland								
Israel				P (94)		P (92)		2
Italy	P	P	P (95)	P (93)	P		P	6
Japan	P	P	P (95)	P (93)	P		P	6
Korea				P (94)				1
Luxembourg								
Netherlands	P	P		P (92)	P		P	5
Mexico							P#	1
New Zealand	P				P (93)		P	3
Norway	P	P (94)	P (95)		P		P	5
Portugal				P (93)				1
Spain			P (95)	P (95)	P	P	P	5
Russia						P (94)		1
Sweden	P	P	P (95)	P (92)	P	WD (91)	P	6
Switzerland	P	P		P (92)	P	P		5
Turkey		P (95)		P (92)	P (93)			3
U.K.	P	P		P (92)	P		P	5
United States	P	P		P (93)	P	P	P	6
E.C.	P (91)	P		P (94)	P		P (96)	5
Total Participants	16	12	8	20	20	7	19	102

P = Participant (yr), WD = Withdrawn, P# Active but not formally signed

Collaborative R & D projects are defined as Annexes to the IEA Wind Implementing Agreement, and are often referred to as Tasks. Each Task has specific objectives, membership, and a budget covering both financial and in-kind commitments from participating members. Each Task is managed by an Operating Agent from one of the participating countries, and the results of the R & D are shared among the participants. A typical Task involves the equivalent of about ten person-years of effort. To date, IEA Wind has undertaken sixteen international collaborative Tasks in areas such as:

- resource characterization, assessment, and modelling
- aerodynamics and interactions between wind turbine rotors
- structural dynamics and fatigue of wind turbine components
- decentralised (off-grid) applications of wind energy
- feasibility and economics of off-shore windfarms

CURRENT ACTIVITIES

There are currently four on-going Annexes as outlined below:

ANNEX XI: BASE TECHNOLOGY INFORMATION EXCHANGE
(Operating Agent: Technical University of Denmark)

Most IEA Wind Member Countries participate in this Task. Its objective is to promote wind turbine technology by cooperative activities and information exchange on R & D topics of common interest. The Task has the following three subtasks:

1. Development of Recommended Practices for Wind Turbine Testing and Evaluation
To date Recommendations have been published in eight areas, and three more are in preparation.
 - POWER PERFORMANCE TESTING
 - ESTIMATION OF COST OF ENERGY FROM WIND ENERGY CONVERSION SYSTEMS
 - FATIGUE LOAD CHARACTERISTICS
 - MEASUREMENT OF NOISE EMISSION
 - ELECTROMAGNETIC INTERFERENCE
 - STRUCTURAL SAFETY
 - QUALITY OF POWER
 - GLOSSARY OF TERMS
 - (POINT WIND SPEED MEASUREMENTS)
 - (NOISE EMISSION MEASUREMENTS)
 - (LIGHTNING PROTECTION OF WIND TURBINE GENERATOR SYSTEMS)

2. Joint Actions

Joint Actions are focussed on research areas where no specific task can be defined, but where members are interested in periodic exchange of technical information, typically every year or two. Joint Actions have been initiated in four areas:

- AERODYNAMICS OF WIND TURBINES
- FATIGUE OF WIND TURBINES
- OFFSHORE WIND SYSTEMS

- WIND CONDITIONS / TURBINE LOADS

3. Experts Meetings

27 Topical Expert Meetings have been held over the past nineteen years on a wide variety of specialist subjects, including recent meetings on: environmental effects on safety, fatigue, design wind conditions, and lightning protection. These meetings are designed to encourage exchange between specialists who are invited by their member countries to participate. Topics are selected by the IEA Wind Ex Co.

ANNEX XIV: FIELD ROTOR AERODYNAMICS

(Operating Agent: Stichting Energieonderzoek Centrum, Netherlands)

The objective of this Task is to coordinate measurements and exchange data from atmospheric tests on blade forces and pressure distributions on different operating wind turbines by five participants in four countries. This Task, almost completed, will result in an extensive data base formatted for convenient use in turbine research and for aerodynamic model development. The data will be available to participants on CD-ROM.

ANNEX XV: ANNUAL REVIEW OF PROGRESS IN THE IMPLEMENTATIONS
OF WIND ENERGY BY THE IEA MEMBER COUNTRIES

(Operating Agent: Energy Technology Support Unit, Harwell, UK)

The Task objective is to produce an annual review of the progress in the commercial development of wind turbine systems in participating IEA member countries. The data are presented in a format suitable for decision makers in government, planning authorities, electrical utilities, financial institutions and the wind energy industry itself. Efforts are underway to initiate a new sub-task to collect and analyze performance data from selected windfarm projects in member countries as well as in developing countries. This is being done in cooperation with the World Energy Council and the World Bank.

ANNEX XVI: WIND TURBINE ROUND-ROBIN TEST PROGRAMME

(Operating Agent: National Renewable Energy Laboratory, USA)

This Task was initiated in 1996 to evaluate wind turbine testing procedures at several test stations in member countries in order to resolve discrepancies and to improve testing methods and procedures. Rigorous experimental procedures include wind tunnel calibration of anemometers and site calibrations of other measuring equipment prior to actual tests on the "standard turbine" (an AOC 15/50).

A new Task: ANNEX XVII: WIND CHARACTERISTICS

(Operating Agent: Denmark)

has been proposed to the IEA Wind Ex Co in the Fall of 1996. Its objective is aimed at identifying, obtaining, and providing research-grade observational wind data sets for a selection of typical site topographies. Such data would be used in improving wind turbine and system design. This Task will be done in cooperation with the European Commission project to compile similar data.

CURRENT TRENDS

During the twenty years since the formation of IEA Wind, wind energy has matured from a research activity to a viable and significant energy supply technology. Globally, the demand for energy continues to increase exponentially, especially in populous nations with traditionally very low per-capita consumption. By the year 2010 China's energy consumption will exceed that of the United States, yet the Chinese per-capita consumption will still be only a small fraction of that in western countries. Moreover, strengthening concerns for the environment will favour non-polluting and non-depletable energy sources. Wind energy is already the most viable of the sustainable energy technologies and extensive worldwide deployment is a certainty.

The IEA has been tracking the world-wide expansion of wind energy development for several years. At the end of 1994 the global installed capacity of wind turbines was 3.5 gigawatts (GW). This grew to 4.9 GW in 1995, and reached 6.2 GW at the end of 1996. Based on individual country projections, deployment should rise to 12 GW by the end of the year 2000. IEA has not developed estimates beyond 2000 AD, but the World Energy Council (WEC) has estimated further increases to 2020. WEC also forecasts an "environmentally driven scenario" that has much faster growth if national policies were adjusted to achieve environmental goals.

Developing countries will play an increasingly important role in this expansion. For example, during 1995 and 1996 India commissioned over 700 MW of wind-electric generating capacity - more than the total global deployment of wind energy up to 1984. Therefore, it is clear that if IEA Wind is to further its support of worldwide utilisation of wind energy, it must broaden its focus from R & D to include issues influencing deployment and operation. This could be done through expanded relations with financial institutions, regulatory agencies, and government / private electric utilities, as well as by maintaining closer collaborations with wind turbine manufacturers, systems analysts and windfarm developers.

FUTURE ROLES AND ACTIVITIES

Future roles and activities will continue to exploit IEA Wind's three principle features:

- **Knowledge**
Through its members, IEA Wind has access to all major public and private sector performers in wind energy technology
- **Strength**
Through the combined efforts of several nations, IEA Wind can plan, support, and undertake projects beyond the capability of any single country or group
- **Neutrality**
IEA Wind has no nationalistic orientation: its sole motivation is the improvement and appropriate deployment of wind energy technology worldwide.

Strategic Reviews of IEA Programs

IEA Wind Ex Co has previously conducted two Strategic Reviews and has initiated that process again. The first review was done in 1987, 10 years after the Agreement was signed. A major result was the decision to merge the Implementing Agreement for Large Scale Wind Energy Conversion Systems and the Implementing Agreement for Research and Development on Wind Systems into one Agreement titled "Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems". A second Strategic Review completed in 1993 with the following directions:

- defined new areas for continued co-operation and information dissemination
- encouraged increased participation of industry and utilities
- suggested extending the co-operation to non-participating countries and to the European Commission
- proposed periodic review of work under the Agreement, and possible completion in 1999

FIGURE 2: WIND ENERGY DEVELOPMENT WORLDWIDE

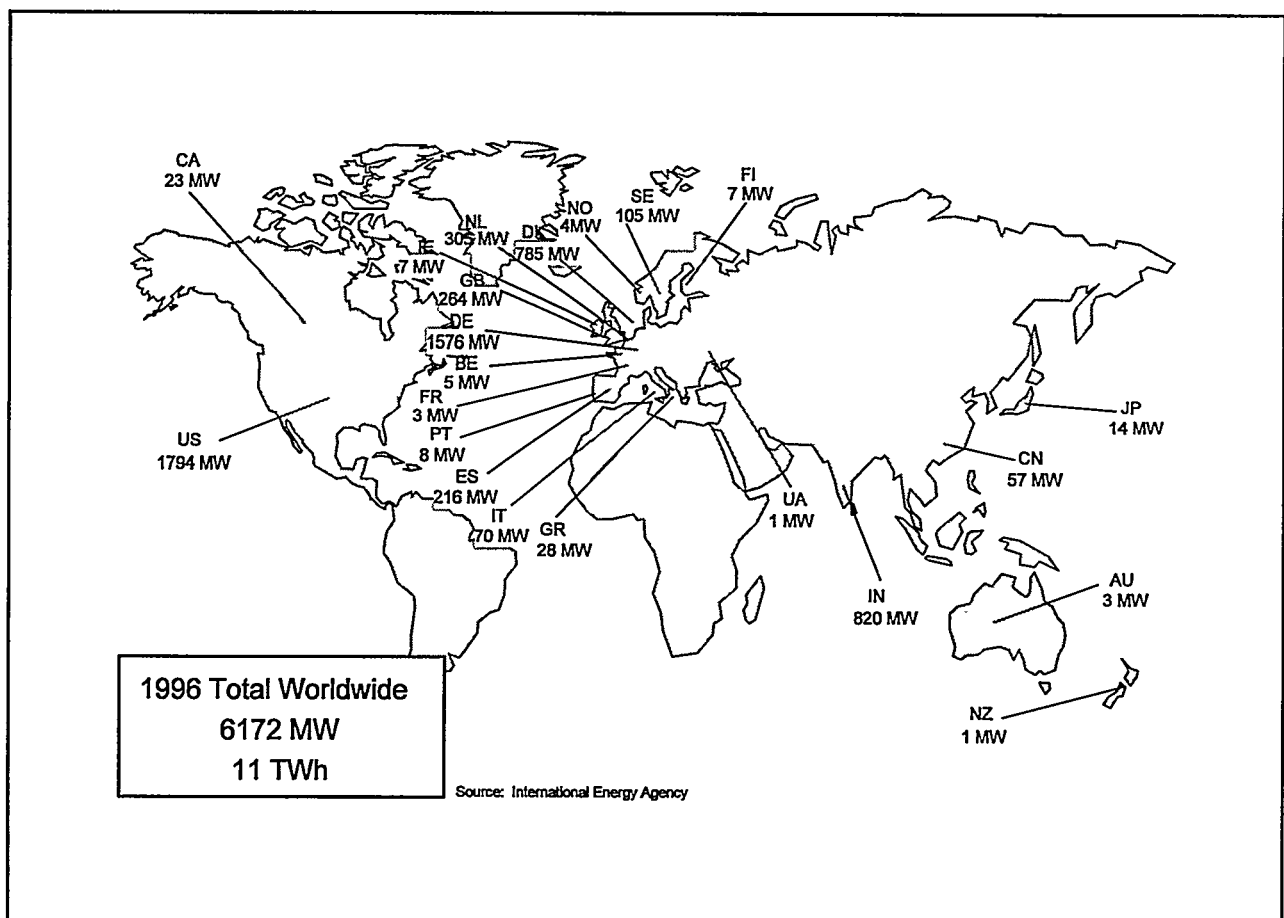


TABLE 2: WIND ENERGY DEPLOYMENT - History and Projections

YEAR	NORTH AMERICA	EUROPE	REST OF WORLD	TOTAL GW	TWH
1990	1.53	0.47	0.02	2.02	4.0
1995	1.77	2.48	0.60	4.85	10.0
2000	2.7	5.3	4.0	12.0	29.0
2010*	30.5	17.0	17.0	64.5	129.0
2020*	93.5	48.0	46.5	188.0	376.0

* World Energy Council estimates

A third Strategic Review of the IEA Wind Program is now underway. This will be completed early in 1998. Currently identified strategic directions for IEA Wind during its next five-year term include:

- continuation of research and development activities to improve wind turbine performance, reduce manufacturing and operating costs, and thereby reduce the cost of wind generated electricity
- increased emphasis on facilitation of deployment of wind energy systems
- transfer of knowledge to non-member nations

However, this review will also consider the following questions:

1. Objectives of the Agreement - How to balance the need for continued cooperative R&D but also to encourage technology deployment.
2. Needs and Target Groups - With which organizations should IEA collaborate and what information do they need that can be produced by the IEA?
3. Means - Are there ways in which IEA can work better and quicker?
4. Role/Position - Are there roles that IEA should play in efforts to accelerate the development and deployment of wind technology?
5. Organizational and Financial - Should the structure of the Agreement change, and are resources allocated to efforts appropriately?
6. Term of the Agreement - Should the Agreement be extended into the next century?

The Ex Co would like to have input to the review process from industry and other organizations. As part of this effort it was agreed to stimulate discussion by presenting papers on the IEA program at both the American and European Wind Conference held during 1997. At these

meetings, input and ideas will be collected and incorporated into the review process and future program plans.

Perhaps the most significant new mechanism of future roles for IEA Wind will be increased collaboration with other international organisations. In 1994, the European Commission joined IEA Wind, reflecting their considerable support for, and involvement in, wind energy research, development and deployment projects in Europe. During 1996, the World Bank approached IEA Wind (through the REWP) and representatives of the Bank have attended IEA Wind Ex Co meetings. At the World Bank's request, IEA Wind has prepared a Theme Paper on the basic techno-economics of wind energy systems which is currently under review at the Bank, and is preparing two Issues Papers on grid-connected and off-grid applications.

To consider plans for supporting the World Bank and other multi-lateral organisations, the Ex Co established an ad-hoc Task Force to explore ways to encourage the development of wind energy in non-OECD countries. This Task Force has completed its work and has recommended the following:

1. That the Agreement should encourage participation of non-OECD countries that have wind energy programs. This will be facilitated by streamlined procedures adopted by the IEA Governing Board in January 1997, for approval of non-Member Country participation.
2. Conditions for joining the Implementing Agreement are to:
 - support a national wind energy R & D program
 - participate in at least one IEA Wind Annex
 - contribute to the Ex Co common fund
 - contribute an agreed share to all Annexes joined
3. Consider establishing a new Annex to encourage the deployment of wind systems in both grid connected and off-grid applications in non-OECD countries.
4. Encourage the Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET) to provide wind project financial data for the World Bank and other financial institutions.

Clearly, there is also a need for continuing research and development to further enhance the performance of wind turbines and to reduce the cost of wind generated electricity. To date, the majority of wind energy R & D has been supported by government agencies. With maturity and commercialisation of wind energy technology, the onus for continued R & D must fall increasingly on the private sector manufacturers and major users of wind energy systems. If IEA Wind is to continue facilitating international R & D collaborations, it must find mechanisms to enable private sector involvement in such projects while respecting proprietary and new market information.

The burgeoning demand for energy in developing countries provides a huge potential market for wind turbines. Unfortunately, wind resource data in many of these areas is sparse, often unreliable, and seldom compiled in ways of most use for assessing potential wind energy installations. Ultimately, a global wind resource atlas should be prepared, possibly in conjunction with atlases of other renewable energy resources. An Experts Meeting will be held in the Autumn of 1997 to discuss actions and options for a possible Task in this area. As a more modest initial

step, IEA Wind is planning to compile detailed wind characteristics at typical sites in the participating countries. High resolution, time series wind speed measurements for several typical topographies would comprise a data base for use by all participants in the design of new turbines for operation in a variety of environments.

The worldwide nature of both wind turbine suppliers and wind turbine markets emphasises the need for internationally recognised guidelines and standards, ranging from resource assessment techniques to turbine design and testing procedures. IEA Wind has already published a number of such documents as listed previously. These are gaining acceptance throughout member nations, but to remain credible they must be kept current and their availability and usefulness must be made known to wind energy officials in non-OECD and developing countries.

Another element of IEA, CADDET prepares and distributes data on all types of energy technology demonstration and deployment projects. IEA Wind, in collaboration with CADDET, could provide reports on the performance of windfarm projects and other data produced by Annex XV. Such information would be useful to both OECD and non-OECD nations contemplating wind energy installations. Information from the IEA Wind Agreement is already made available through its Annual Report and through its periodic (free) Newsletter, and also on the World Wide Web at the address:

<http://www.eren.doe.gov/ieawind/>

SUMMARY

For the past twenty years IEA Wind has emphasised international collaboration in the research and development of wind energy technology. This emphasis will continue with added effort focussed on issues relating to worldwide deployment, where IEA Wind's knowledge, strength, and neutrality can aid in the assessment and execution of wind energy projects. New challenges for IEA Wind include closer collaborations with multilateral international institutions, dissemination of knowledge to non-OECD and developing nations, and creation of mechanisms to interface with private sector performers.

French Wind Power Generation Programme EOLE 2005 - First Results

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ABSTRACT : EOLE 2005 has been launched in July 1996 by the French Ministry of Industry, Electricité de France and ADEME (Agency for Environment and Energy Management). The Ministries of Research and Environment are participating also in this programme. The purpose is to create an initial market in France for wind power generation in order to evaluate the cost-effectiveness and the competitiveness of the wind energy compared to other energy sources by 2005. The installed capacity will reach at least 250 MW and possibly 500 MW.

1 - BACKGROUND

The development of wind energy in Europe during the 80s and 90s has been performed mainly in countries operating largely fossil fired power plants and with a moderate amount of the renewable energy. The installed capacity of hydraulic power, 25000 MW (23500 MW by EDF) and the production of 70 TWh electricity (17% of national consumption) by a cost-effective renewable energy, did not help to promote the development of wind energy in France during this period. Fossil fired power plants produce 5% of the total electricity in this country. The total installed capacity is also large enough to ensure the national consumption and the EDF exports to other countries. So there is no need for more capacity and the EDF kWh price is one of the lowest in Europe.

Nevertheless the first experiences of wind energy in France goes back to some forty years ago. Promoted by EDF in the years 1958 to 1962 the first MW class wind turbines were installed at Nogent Le Roi (800 kW) and at St. Remy des Landes (1000 kW). In the seventies the French Atomic Commission carried out some experiments. In the late seventies some French manufacturers (Aerowatt and Ratier-Figeac) with EDF and ADEME (Agency for Environment and Energy Management) collaboration installed a few machines (100 - 150 kW). These experiences were not very successful. The material and the design tools used at that time were of course very far from the current know how in this field.

1996 was a turning point for wind energy in France. In this year, EDF, the French Ministry of Industry, and ADEME decided to collaborate in order to develop 250-500 MW of wind power over the next ten years in France. The wind farms are to be installed and operated by independent power producers chosen through a tendering procedure.

EDF is also involved in another important project in Morocco (Tetouan) to develop a 50 MW wind farm to be commissioned in the early 1998. There are other projects with EDF participation : 2.7 MW Dunkerque wind plant which is in operation since December 96 and 7.5 MW project at Salsigne to be installed by the end of 1997.

A joint R&D programme has been launched at EDF R&D Division in order to provide the Company with all the necessary up to date know how for managing and operating this programme. This includes a world wide technical monitoring of wind energy, development of software to calculate the wind potential, studying grid connection issues and wind energy production costs.

2 - OBJECTIVES

The French EOLE 2005 programme for the next 10 years is quite important (between 250 and 500 MW). The objectives of this programme are :

- to assess the cost-effectiveness and the competitiveness of the wind energy compared to other energy sources by 2005,
- to create an initial market in France for wind power generation in order to help the groups of companies including French developers and manufacturers having their references in France for export projects. The world market represents 1300 MW per year now, increasing up to 2000 MW per year in the beginning of the next century, according to current estimates.

The challenge for wind energy is not finished yet. In many European countries wind power plants have been installed for political reasons or for preparation for the future with incentives and grants. This policy has permitted the development of a mature technology with kWh cost almost at break-even point for the best sites. Further progress in the near future could only be imagined on an economical basis with or without very moderate incentives, especially if some consumers accept to pay slightly more for the wind energy.

Therefore wind energy has to confirm its competitiveness with other energy sources in the near future. The electricity cost for the most recent conventional power plants (Combined Cycles) is near 3.5 cents /kWh and will decrease with the steady improvement of technologies.

For under developed countries, where there is a real need for new capacity now, the kWh price is one of the most important criteria for choosing a power plant. From 2005-2010 a lot of conventional power plants will have to be replaced in European countries. At that time the competition will be very tough between different energies.

So there is a real need to reduce wind energy production costs. The wind energy technology has to be improved but it could be considered temporarily mature, allowing focus on cost reductions. Recent development of the market could also help the manufacturers to reduce prices. Joint ventures between different industries may also be necessary to achieve this objective. The potential French manufacturers are trying also to adopt strategies including a close collaboration with the existing wind industry in Europe. These collaborations will permit them also to take advantage of the present technological know how in Europe.

3 - CALL FOR TENDERS' PROCEDURE

3.1 - Object

In the framework of the EOLE 2005 programme, Electricité de France, in collaboration with the French Ministry of Industry, and ADEME has launched a first request for proposals in order to provide 50 MW of wind power in France generated by installations owned by independent power producers.

The request for proposals contains two sections. The first, approximately 15 MW, was set aside for wind power producers who had already measured the wind potential of their sites. The second part, 35 MW, was open to applicants who equipped their sites with measuring systems by October 31, 1996.

3.2 - Preselection of the applicants

The companies or the group of companies wishing to propose a project in the framework of this call for tenders had to apply for participation. EDF, the involved Ministries (Industry, Environment and Research) and ADEME proceeded to a preselection on the bases of the documents provided by the applicants. A tender pack was sent to each preselected applicant.

The preselection criteria measure the capacity of the applicants, their partners and their suppliers to carry out a wind project. The necessary guarantees had to be provided in the following domains :

- Qualifications level :
 1. Technical references on wind turbines or their components,
 2. Quality Assurance or certification of wind turbine and/or components,
 3. References on carrying out wind farm projects (sites and installed power, commissioning date) or other comparable industrial projects,
 4. Wind farm operation references (sites and installed power, commissioning date and availability of wind turbines) or other installations of electricity generation.
- Financial capacity to carry out a wind project.

3.3 - Projects selection criteria

The projects selection criteria are as follows :

- Purchasing price of kWh requested by the applicant
- Economic advantages of projects
- Long term benefits of the chosen technical solutions
- Technical and financial reliability
- Respect for the environment
- Opinion of local and regional authorities

Furthermore, a certain diversity, concerning regions of installation as well as types of wind turbines used, has been taken into consideration in the selection procedure.

It is important to choose projects which are scattered in the whole country so far as possible, in order to avoid the concentration of many wind farms in a limited area. The public acceptance is particularly improved if we could maintain this position for the whole programme.

A large distribution of the projects is necessary, but not in areas where the wind resources are very limited. One of the main objective of this programme is to show the cost effectiveness of wind energy, and the projects in less windy areas could constitute a negative reference. In medium ranged wind resources, subsidies from different authorities could help the projects to be selected but it is important, for the future of this field, to choose the projects which could be viable economically.

It is important to have qualified machines with proven technologies in this programme. Meanwhile a few projects using innovative technologies could exceptionally be accepted if respecting the above mentioned criteria.

The power of each wind farm will be situated between 1.5 MVA and the French legal upper limit of 8 MVA.

3.4 - Relevant territories

The wind farms could be installed on any French territory, on the continent and in overseas departments served by EDF on the basis of public distribution concession.

3.5 - Key dates

The closing date for answering to the preselection was October 1, 1996.

The closing date for submission of the first section tender was December 31, 1996.

The closing date for submission of the second section tender was May 31, 1997.

4 - RESULTS OF THE FIRST SECTION (15 MW)

The following projects have been selected among 20 propositions received by the Selection Committee for the first part of call for tender :

- Widehem site (Pas-de-Calais - North of France) a wind farm of 4,5 MW proposed by **Jeumont Industrie/Micon**,
- Donzère site (Drôme - South of France) a wind farm of 3 MW proposed by **Spie Trindel/Bonus**,
- Petit Canal (Guadeloupe - French overseas island) a wind farm of 2,4 MW proposed by **SIIF/Vergnet**,
- Lastours (Aude - South of France) a wind farm of 3,05 MW proposed by **Vergnet/Nordex/Lagerwey/Dewind/Enercon**.

4.1 - Analyse of the tenders

Figure 1 shows the position of the 3 selected sites on the continent in France. The one in Guadeloupe is illustrated in figure 2. Figure 1 shows also the order of magnitude of wind resources in France according to RISØ [1]. The selected projects are located in good and medium range wind resources.

As could be seen from this figure these projects are well dispersed in the whole country. The technologies are also quite different from one project to another. This is also helpful for feedback experience that we have to perform by the end of this programme.

French industry is very active and collaborates with other European manufacturers to take part in this programme. The collaboration of Jeumont Industrie with Micon and Vergnet with Nordex, Lagerwey, Dewind and Enercon are showing good examples of European turbine construction.

On the other hand the environmental aspects in some of the propositions are not studied enough. In the specifications this part is developed largely and we hope to select the projects that could easily satisfy environmental impact assessment and obtain all the authorisations.

The average kWh prices for the 4 projects selected is 6.7 cents. This is higher than the one announced for NFFO4 programme in England and Wales (5.6 cents). This could be explained by lack of experience of French developers and short time for preparing the propositions for the first section. We hope to obtain better results for the second section of call for tenders.

Figure 3 represents the kWh prices proposed by the applicants compared to the analyses performed by EDF in 1996 [2]. The wind turbine market is changing rapidly and the costs presented in the paper are based on some average values of the prices, published in 1994 and 95. The EDF estimations are obtained for some average conditions and real projects could not of course follow the evaluations closely but the dispersion is quite important. The operation and maintenance costs seems to be very often overestimated as well as some extra charges like impact studies, engineering, transport and sometimes grid connection costs. Different financial arrangements are not very well used by the developers.

Figure 4 illustrates the kWh prices as a function of installed capacity. The wind resources depend on projects and some dispersion is normal. But if the mean speed is also added in this curve (for confidential aspects of the call for tenders it is not possible to publish it) no correlation could be found. Increasing the installed capacity did not reduced the kWh price. The range of variation of installed power (mostly between 2 and 5 MW) is not enough to modify significantly the kWh price.

5 - CONCLUSIONS

The French wind generation programme EOLE 2005 and the first results obtained are discussed. We have tried to present more specially the EDF strategy on wind energy and the way we prepare for the future. The programme will allow the cost effectiveness and the competitiveness of the wind energy to be thoroughly assessed.

Four projects have been selected for the first section of the call for tenders. These projects are well dispersed in the whole country. The average kWh price of 6.7 cents is obtained. This is approximately 18% higher than the one announced for the NFFO4 programme. For the second section of the programme the average price could be less. The wind turbines used are from different technologies and gives enough

matter to study for the future. The range of turbine rated power varies from 60 kW (tilt-down tower from Vergnet for Guadeloupe) to 1200 kW (MW class from Nordex for South of France). The range of projects and turbines will allow significant comparisons and assessment, with important feedback into following stages of the wind energy programme in France.

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Figure 1 - Location of three selected projects in France (on the continent) -
Wind resources from RISØ [1].

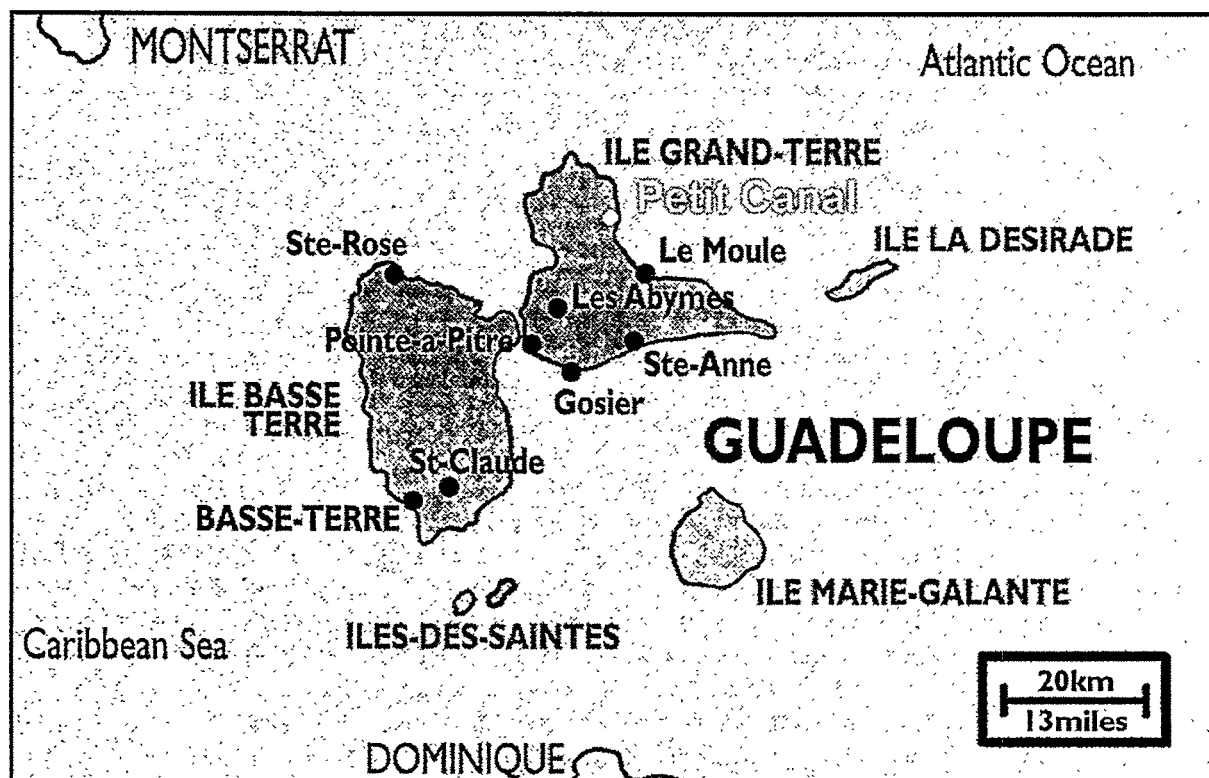


Figure 2 - The location of the fourth project in Guadeloupe

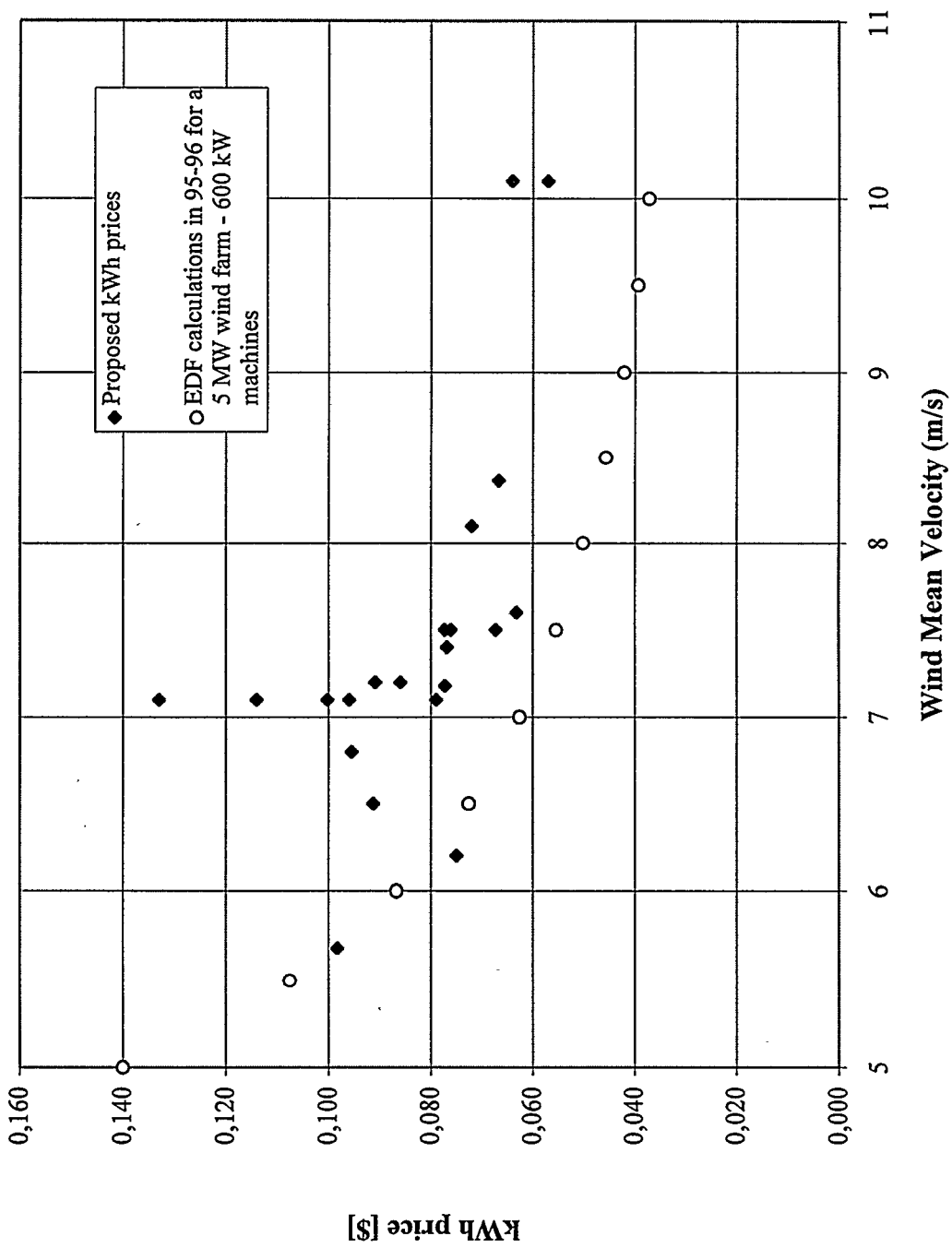


Figure 3 - kWh price as a function of wind mean velocity

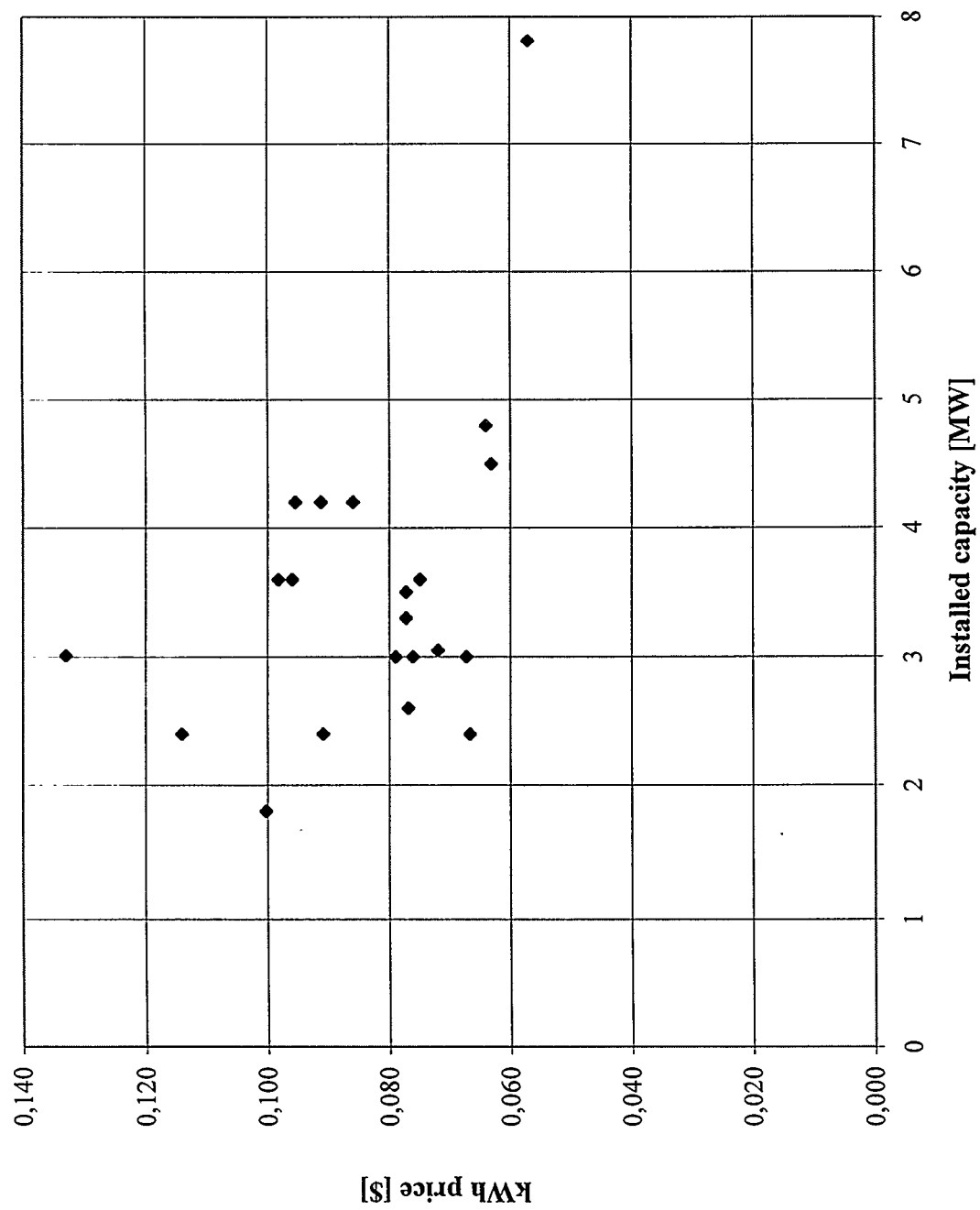


Figure 4 - kWh price as a function of installed capacity

DOE-EPRI DISTRIBUTED WIND TURBINE VERIFICATION PROGRAM (TVP III)

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In 1992, the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE) initiated the Utility Wind Turbine Verification Program (TVP). The goal of the program is to evaluate prototype advanced wind turbines at several sites developed by U.S. electric utility companies. Two six MW wind projects have been installed under the TVP program by Central and South West Services in Fort Davis, Texas and Green Mountain Power Corporation in Searsburg, Vermont. In early 1997, DOE and EPRI selected five more utility projects to evaluate distributed wind generation using smaller "clusters" of wind turbines connected directly to the electricity distribution system. This paper presents an overview of the objectives, scope, and status of the EPRI-DOE TVP program and the existing and planned TVP projects.

TVP GOALS, OBJECTIVES, AND SCOPE

EPRI and DOE established the Wind Turbine Verification Program in 1992 to provide a bridge from utility-grade turbine development programs underway to commercial purchases of wind turbines (1). The overall TVP goal is to facilitate development and installation of utility wind projects in order to both help utilities get wind power experience, and build and operate enough candidate turbines to obtain statistically significant operating and maintenance data.

The specific objectives of TVP include:

- Verifying the performance, reliability, maintainability, and cost of new wind turbine designs and system components in a commercial utility environment.

- Providing states, utilities, and other stakeholders with a valid opportunity to test and evaluate wind power in new areas.
- Creating modest turbine markets and development opportunities during the next five years.
- Documenting and communicating the experience from these projects for the benefit of utilities, independent power producers, other nonutility generators, landowners, wind turbine suppliers, and others in the wind power development community.

EPRI manages the TVP program on behalf of DOE, itself, and the host utilities, and works closely with the National Renewable Energy Laboratory (NREL) to provide technical guidance to the TVP projects. The TVP projects are funded by contributions from EPRI, DOE, and the host utilities.

TEXAS AND VERMONT TVP PROJECTS

The first two TVP projects were selected by a formal competitive solicitation issued by EPRI in 1993: the 6.6 MW Central & South West Services (CSW) project in Fort Davis, Texas, with 12 Zond Z-40A wind turbines; and the 6.0 MW Green Mountain Power Corporation (GMP) project in Searsburg, Vermont, with 11 Zond Z-40FS turbines. The projects are funded by EPRI, DOE, and utility cost sharing, which covers project development, installation, acceptance testing, and operation for three years.

Turbine installation was completed at the CSW project in 1996, and the three-year TVP operating period began in July 1996. The project development experience at the CSW project is documented in a recent EPRI report (2). At the GMP project, turbine installation was completed in December 1996, but gearbox problems encountered during acceptance testing have delayed commissioning of the project until July 1997 (3). The three-year test programs for both projects include turbine performance verification testing; collection of availability, operation and maintenance, wind resource, and other data; and technology transfer of the results via published EPRI operations reports and annual TVP workshops (4).

DISTRIBUTED WIND GENERATION

The business environment for the electric-power and wind-turbine industries has changed markedly since the initiation of the TVP in 1992. Although wind power is rapidly expanding in overseas markets, the domestic market has slowed considerably. The role and interest of U.S. utility companies in owning and operating wind turbine facilities have changed, due to a combination of low-cost surplus power availability and uncertainty about the

effect of industry restructuring on utilities' role in owning and operating generation assets.

Relative to the large wind farm concept, distributed wind generation using "clusters" of wind turbines offers a lower-risk and more flexible way for utilities to participate in wind energy projects. Such projects would typically be connected directly to a distribution line without a substation and operated independently or from a central remote site. This is in contrast to most existing U.S. wind power plants, where large numbers of turbines are located at a single site, operation and maintenance services are provided from a nearby facility, and the power collection system requires a substation and transmission line interconnection. In addition, the distributed generation concept offers promising opportunities for utilities to address system expansion issues and better serve customer needs. It allows location of smaller, modular capacity assets nearer to load centers, as an alternative to the traditional approach of expanding centralized generation.

These trends suggest that a likely near-term market for development of wind power resources is relatively small, distributed groups or clusters of wind turbines, owned and operated by a broader spectrum of utilities and other organizations, including electric cooperatives, municipal utilities, independent power producers, other nonutility generators and landowners.

As a result, DOE and EPRI added a new dimension to the TVP program in 1996 to focus on distributed wind turbine projects. In addition to the existing TVP objectives discussed earlier, the objective is to evaluate the benefits and impacts of distributed wind turbine (DWT) projects connected directly to the electricity distribution system, with specific focus on:

- The value and performance of DWT projects as generating resources in competitive power markets under different system conditions.
- The required hardware and O&M characteristics for DWT projects.
- The difference in preferred turbine performance and O&M cost characteristics between DWT projects and large wind farm projects.

TVP III DISTRIBUTED WIND GENERATION PROJECTS

In early 1997, DOE and EPRI selected five new distributed wind generation TVP projects via a competitive solicitation issued by EPRI in August 1996 (5). The solicitation was open to any U.S. organization or consortium of organizations involving municipal, rural, cooperative, government, investor-owned utilities, or independent power producers. The host utility could either own and operate the wind facility or purchase power from a third party, such as an independent power producer or nonutility generator.

However, the host utility was expected to submit the proposal to EPRI and serve as the principal contracting organization and project manager.

Table 1 summarizes the participants, wind turbine design, and wind resource characteristics; and Figure 1 shows the locations of the five selected TVP III projects. The host utilities include Cedar Falls Utilities, Nebraska Public Power District, City of Brownfield (Texas), Central and South West Services, and Niagara Mohawk Power Corporation. The projects represent a range of utility types (municipal, public power, and investor-owned utilities), wind turbine design, and geographical and electricity-distribution-system characteristics. In addition, two other projects participate as "associate" members of the TVP III program: the Wisconsin Low Wind Speed Wind Turbine Project near Green Bay, Wisconsin, and the Kotzebue Electric Association Wind Farm Project in Kotzebue, Alaska.

As described further below, the five selected projects involve project planning and development; turbine procurement, installation, acceptance testing, and operation for two years after turbine acceptance; turbine performance and operating data collection and analysis, and distributed generation and power quality evaluations.

Iowa Distributed Wind Generation Project

The host utility of the Iowa project is Cedar Falls Utilities. The project site is in Algona, Iowa in the north-central part of the state and in the service territory of Algona Municipal Utilities, which will also maintain the turbines. Other participants include five other Iowa municipal utilities, which will also own portions of the project; and Zond, which will supply three 750 kW Z-50 turbines to the project. The additional municipal utility participants include Ellsworth, Esterville, Fonda, Montezuma, and Westfield, Iowa. The Zond Z-50 turbine is a variable-speed machine using a 50-meter rotor and a 50-meter tower. The annual average wind speed at the project site is estimated to be 7.1 m/sec (15.9 mph), and the annual power generation is estimated to be 1.8 million kWh/yr/turbine. Site preparation and turbine order will occur during 1997, and the turbines are expected to be operating by third quarter 1998.

Nebraska Distributed Wind Generation Project

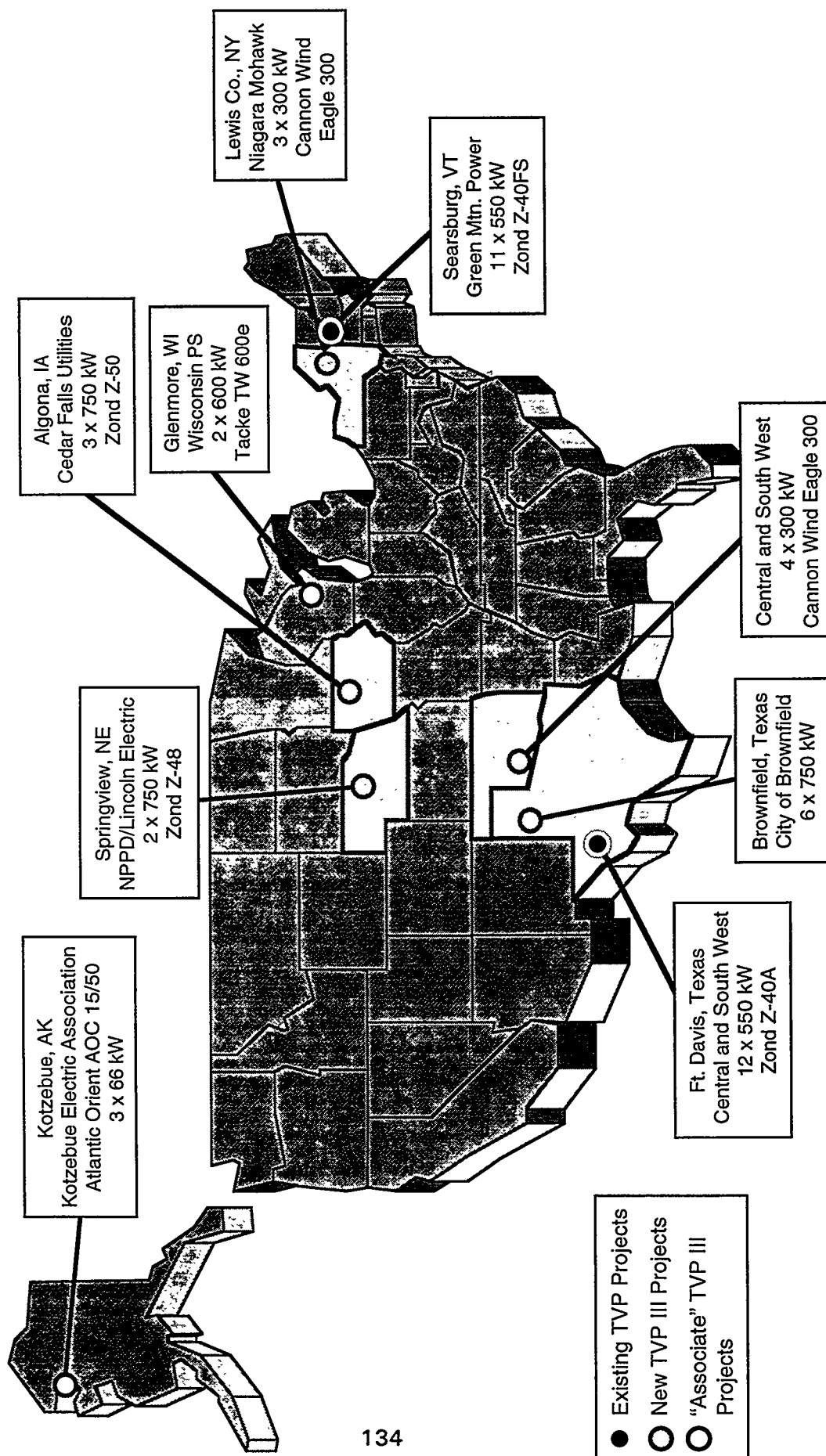
The host utility in the Nebraska project is Nebraska Public Power District, which will manage the project. The project site is in Springview, Nebraska in north-central Nebraska and in the service territory of KBR Rural Public Power District. KBR RPPD will maintain the facility and receive the power output. Other participants include Zond, which will supply two 750 kW Z-48 turbines to the project, and the cosponsors, Lincoln Electric System, the Cities of Grand Island and Auburn NE, and the Municipal Energy Agency of Nebraska (MEAN) and. The Zond Z-48 turbine is a variable-speed machine using a 48-meter rotor and a 50-meter hub height. The annual average wind

Table 1. TVP III Distributed Wind Turbine Verification Projects

Note: Proposed project owner/operators are in bold-face type

Utility	Others	Project Location, Avg. Wind	# Turbines x kW	Turbine Rotor Dia./ Hub Ht.	Turbine Startup
Cedar Falls Utilities	Algona Municipal Utility 5 other IA munis	Algona, IA 7.1 m/sec @ 50 m	3 x 750 kW	Zond Z-50 50 m/50 m	3Q 1998
Nebraska Public Power District	Lincoln Electric System Cities of Grand Island and Auburn MEAN	Springview, NE 7.5 m/sec @ 40 m	2 x 750 kW	Zond Z-48 50 m/50 m	4Q 1998
City of Brownfield	Texas Wind Power Co.	Brownfield, TX 7.4 m/sec @ 55 m	6 x 750 kW	TBA	1Q 1998
Central and South West Services	Texas Wind Power Company Texas State Technical Inst. West Texas A&M	TBD 6.5 - 7.0 m/sec @ 55 m	4 x 300 kW	Cannon Wind Eagle 300 29 m/50 m	3Q 1998
Niagara Mohawk Power Corporation	NYSERDA AWS Scientific	Lewis County 7.0 m/sec @ 50 m	3 x 300 kW	Cannon Wind Eagle 300 29 m/50 m	3Q 1998
<u>"Associate" TVP III Projects</u>					
Wisconsin Public Service	Madison G&E Wisconsin P&L Wisconsin Electric Madison G&E EPRI	Glenmore, WI 6.1 m/sec @ 40 m	2x 600 kW	Tacke TW-600e 46 m/50 m	3Q 1997
Kotzebue Electric Association	NREL	Kotzebue, AK	3 x 66 kW	AOC 15/50	1997

Figure 1 Distributed Wind Generation - TVP Phase III



speed at the project site is estimated to be 7.5 m/sec (16.7 mph), and the annual power generation is estimated to be 2.1 million kWh/yr/turbine. Site preparation and turbine order will occur during 1997 and the turbines are expected to be operating by fourth quarter 1998.

Texas Distributed Wind Generation Project

The host utility in the Texas project is the City of Brownfield, Texas, located in the Texas panhandle. The project site is on City land in the southeastern part of the City. The City of Brownfield will purchase power, Texas Wind Power Company will develop, construct, and operate the project, and the Texas Wind Power is negotiating with a turbine vendor to supply six 750 kW turbines to the project. The annual average wind speed at the project site is estimated to be 7.4 m/sec (16.6 mph), and the annual power generation is estimated to be 1.5 million kWh/yr/turbine. Site preparation and turbine order will occur during 1997, and the turbines are expected to be operating by first quarter 1998.

Central and South West Distributed Wind Generation Project

The participants in the Central and South West project include Central and South West Services, which will own and operate the project; Texas Wind Power Company, which will provide engineering and installation services; and Cannon Power, which will supply four 300 kW Wind Eagle 300 turbines to the project. The Cannon turbine is based on the J. Carter, Sr. light-weight, tilt-up design and will use a downwind, 29-meter rotor and a 50-meter tower.

The project will be conducted in two phases. In Phase 1, the utility will evaluate candidate sites for the project in Oklahoma and monitor a redesign evaluation of the Cannon Wind Eagle 300 turbine. At the conclusion of Phase 1, DOE, EPRI, the host utility and Cannon will review the results of the Phase 1 evaluation and decide whether to proceed with installation, acceptance testing and operation of the wind turbines under Phase 2. It is expected that the Phase 1 evaluation will be completed by early 1998, and that turbine installation can occur later in 1998.

Although the project site has not yet been determined, it is expected that the annual average wind will be in the range 6.5 - 7.0 m/sec (14.5 to 16.7 mph) at the project site, and the annual power generation will be about 0.7 million/kWh/yr/turbine.

New York Distributed Wind Generation Project

The participants in the New York project include Niagara Mohawk Power Corporation, which will own and operate the turbines; AWS Scientific, which will assist Niagara Mohawk; the New York State Energy Research and Development Authority (NYSERDA), which will cosponsor the project; and Cannon Power, which will supply three Wind Eagle 300 wind turbines to the project. The project will be located at a Lewis County site in northern New

York State. Otherwise, the scopes of the New York and Central and South West projects are similar, and the New York project will also be conducted in two phases. The annual average wind speed at the project site is estimated to be 7.0 m/sec (15.6 mph) at 50 meters, and the annual power generation is estimated to be 0.7 million kWh/yr/turbine.

Wisconsin Low Wind Speed Wind Turbine Project

The host utility in the Wisconsin Low Wind Speed Wind Turbine Project is Wisconsin Public Service Corporation. The project site is in Glenmore, Wisconsin, near Green Bay. Tacke Windpower will supply two 600 kW TW-600e turbines to the project. The project is sponsored by EPRI and the four eastern Wisconsin utilities. Besides Wisconsin Public Service, they include Madison Gas and Electric Company, Wisconsin Electric Power Company, and Wisconsin Power and Light Company. The Tacke TW-600e turbine is a two-speed machine using a 46-meter rotor and a 50-meter hub height and is designed to maximize power generation under the low wind speed conditions that exist in Wisconsin. The annual average wind speed at the project site is estimated to be 6.1 m/sec (13.7 mph), and the annual power generation is estimated to be 1.8 million kWh/yr/turbine. Turbine installation and acceptance testing will begin in August 1997. Data gathering will continue for five years after turbine acceptance.

Kotzebue Electric Association Wind Farm Project

The participants in the Kotzebue project include Kotzebue Electric Association, which will own and operate the facility, and Atlantic Orient Corporation, which will supply three 66 kW AOC 15/50 wind turbines to the project. The wind facility will be connected to the Kotzebue 12.5 kV distribution system and augment the existing diesel generation facilities. As of mid-1997, one turbine is operating, and startup of the other two turbines will occur later this summer, pending arrival of additional blade sets. In addition, Kotzebue Electric is working with NREL, DOE, and Alaskan development agencies to develop one to two MW of additional wind farm and village wind power projects.

TVP III PROJECT RESPONSIBILITIES

The Host project teams for the TVP III projects include the host utility, turbine vendor, and, in some cases, other utility sponsors, project developers, and consultants, as shown in Table 1. The Host is responsible for the basic definition, evaluation, implementation, operation and documentation of the new distributed wind generation facility using the latest prototype advanced wind turbines. DOE and EPRI will assist the Host with ad-hoc issues in the development and evaluation stages of the project to ensure that available expertise is used to help achieve Program objectives. In addition to sharing in the cost of a project, the parties also have the following specific responsibilities:

DOE/NREL: Participate in the development and conduct of the TVP design and evaluation plan; participate in technical reviews; conduct the required NEPA review for each project; provide limited assistance for specific technology issues; participate in technology transfer and program outreach activities; furnish a SCADA unit to each site and operate a central data collection system.

EPRI: Execute the TVP contract with the Host and carry out overall project management; participate in the development and conduct of the TVP design and evaluation plan; participate in technical reviews; approve certain project decisions and reports in connection with progress payment milestones; provide limited assistance for specific technology issues; administer and participate in the technology transfer and program outreach activities; prepare, publish and distribute formal project technical reports.

Host Utility: The host utility is expected to be involved in the following activities: (1) establish the feasibility of the proposed project; (2) prepare and present technical reviews of the project; (3) participate in project technology transfer and Program outreach activities; (4) conduct a baseline noise survey and ensure that avian considerations are addressed prior to the final site selection; (5) provide and operate a meteorological mast or tower at nominal hub height at the site; (6) as owner of the wind facility, hold the rights to the project wind resource and title to the wind turbines, obtain all required project development permits and approvals (except for the NEPA review), and oversee the installation of project equipment, support the interface between the wind turbine and the SCADA system provided by NREL, coordinate operation and maintenance of the SCADA system(s), plan and conduct turbine performance evaluations using the IEC performance test procedures, operate and maintain the project, monitor noise and other project impacts, and prepare technical reports.

TVP III PROJECT SCOPE

The TVP III project scope is designed to: successfully install and operate each distributed wind generation project; evaluate the performance, availability, operation and maintenance of the facility for two years after turbine acceptance; transfer experience and lessons-learned from the existing TVP projects to the new TVP III projects; generate a database of turbine performance and O&M data in a consistent format for the various TVP projects; and communicate the TVP project experience to the utility and wind power industries. The scope of work for each project includes the following activities:

- Negotiate land lease and wind rights agreements; obtain building, FAA, and other required permits; and prepare site for installation of met tower, wind turbines, and other equipment.

- Negotiate agreements with turbine vendor covering turbine purchase, installation, O&M, and equipment, availability and performance warranties.
- Coordinate and maintain the interface between auxiliary SCADA system to be supplied by NREL to each project and the turbine.
- Install interconnection of turbine facility to electricity distribution system at the high side of the step-up transformers on each turbine pad.
- Construct general facilities necessary to complete project, including access roads, identification signs, shelters, and communications lines.
- Operate and maintain the wind turbine facility for at least two years after initial turbine acceptance.
- Obtain turbine performance and O&M data in conjunction with the TVP support contractor.
- Evaluate the impact of the distributed wind generation facility on the operation and future upgrades of the electricity distribution system and on power quality delivered to the utility customers (frequency, voltage, current, power, power factor, harmonics).
- Conduct avian studies during fall and spring migration seasons.
- Participate in TVP III project review meetings.
- Participate in annual TVP Workshops and conduct other technology transfer activities including facility tours, school and civic group presentations, press releases, and regional workshops.
- Provide required documentation including monthly letter reports, informal project reports, turbine vendor monthly reports during project installation, monthly operation and maintenance logs, and other data and other information required by EPRI to prepare reports.

CONCLUSIONS

During 1996, DOE and EPRI initiated the new distributed generation phase of the DOE-EPRI Wind Turbine Verification Program (TVP III). In early 1997, five new TVP projects were selected by competitive solicitation using clusters of two to six turbines. The projects are located in Iowa, Nebraska, New York, and Texas and are expected to be installed during 1998. The scope of each project includes: turbine installation, startup and acceptance testing; collection

of turbine performance, operation and maintenance data for two years; distributed generation and power quality evaluations; technology transfer; and documentation. In addition, two other projects in Wisconsin and Alaska are designated "associate" members of the TVP III program and will also provide turbine performance and operating data to the program. The resulting database will provide consistent and uniform turbine data for a variety of turbine designs, geographical locations, wind resource regimes, and other characteristics.

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INTEGRATING CERTIFICATION INTO THE U.S. DEPARTMENT OF ENERGY/NATIONAL RENEWABLE ENERGY LABORATORY TURBINE RESEARCH PROGRAM

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ABSTRACT

The Wind Turbine Research Program conducted for the U.S. Department of Energy (DOE) by the National Renewable Energy Laboratory (NREL) employs a comprehensive engineering development process which includes regular design, testing, and documentation reviews throughout the process. This process follows accepted international procedures, including the International Standards Organization ISO 9001. International wind turbine certification practice typically requires a review of only the final design and testing results of a wind turbine system. Using this approach, if the design does not meet requirements, the designer is faced with the lengthy and inefficient process of rerunning engineering calculations or tests or even redesigning major components. NREL has recognized the similarity between its development process and international certification practice and has integrated the two. The result is a comprehensive engineering development process, which enables subcontractors participating in the DOE/NREL Wind Turbine Research Program to develop a mature product, which is ready for commercialization and certification.

This paper describes the NREL development process, certification requirements, and the benefits of integrating them together.

INTRODUCTION

International certification has become a requirement for U.S. manufacturers to compete in many foreign markets. At present there are three international certification bodies active in the European wind turbine industry: Germanischer Lloyd (1), Det Norske Veritas and Risø (2) and CIWI (3). Each certification body has developed its own rules and requirements for Type Certification but they generally have the same goal: to review the design documentation and assure that the turbine has been designed with engineering discipline, in accordance with recognized industry standards, and will function reliably throughout its specified life. Most turbines installed in Europe must be certified by one of these bodies to its own set of rules and requirements.

Over the past five years, the European Community (EC) has encouraged harmonization of the different certification rules in order to facilitate trade within Europe. This has resulted in active standards development programs on the international level. The International Electrotechnical Commission (IEC)

has supported the development of several standards, which will hopefully be the basis for a set of harmonized standards. These include

1. Wind Turbine Generator Systems: Certification Requirements [WG9 tenth Committee Draft (10CD)] Wind Turbine Generator Systems: Safety of Wind Turbine Generator Systems (IEC 1400-1 Edition 2) [WG7 , Final Draft International Standard (FDIS) sent out for national vote]
2. Wind Turbine Generator Systems: Safety of Small Wind Turbine Generator Systems (IEC 1400-2 [FDIS])
3. Wind Turbine Generator Systems: Power Performance Measurement Techniques (IEC 1400-12) (WG6 FDIS)
4. Wind Turbine Generator Systems: Acoustic Noise Measurement Techniques (IEC 1400-11) (WG10 FDIS)
5. Wind Turbine Generator Systems: Testing Methods for Rotor Blades (IEC1400-23) (WG8 CD)
6. Wind Turbine Generator Systems: Power Quality Requirements for Grid Connected Wind Turbines (IEC1400-21)(WG10 CD)
7. Wind Turbine Generator Systems: Mechanical Load Measurement Techniques (IEC1400-13) (WG11 CD).

While each European country's certification procedures depend on national requirements, the above international standards will be the basis for an international certification procedure, as described in item 1 of the above list.

IEC 1400-1 specifies "external conditions" (wind and environmental) and normal and abnormal operating conditions that must be satisfied for different design classes. ISO quality (17, 18, 19) and limit state design (20) procedures are also specified and clarified for the wind turbine design application. European certification bodies will take a step towards harmonization by adopting this standard in addition to their own national requirements in the future by law.

Wind turbine certification is not required by U.S. utilities, customers, or local governments. As a result, most U.S. turbine manufactures have not pursued certification. Now that the international market is stronger than the domestic market, there is greater interest from U.S. manufacturers to certify their wind turbines. However, there is no U.S. certification body nor is there an established set of standards on which to base a certification process.

The American Wind Energy Association (AWEA) has been active in developing national standards for 15 years. This process has resulted in useful standards but they are not used by the international community because it is felt they are not sufficiently prescriptive. AWEA has decided to support the IEC standards development process as these standards will be valuable for international marketing.

Several U.S. companies have participated in the DOE/NREL Turbine Research Program (TRP). This program has a well-established design review process with regular design reviews and test readiness reviews as prototype turbines evolve from conceptual to final design stages. In many ways this program parallels European certification programs. With minor modifications, the TRP has aligned its requirements to match the IEC certification requirements. Companies who participate in this program can now expect to finish the program with all the documentation and reviews needed to satisfy the IEC certification requirements as they are developed.

DOE/NREL TURBINE RESEARCH PROGRAM

There has always been debate on how to approach the wind turbine design and development process. Some favor an analytical approach with very little testing. In this case, testing is used only as a verification of the final design analysis predictions. Others favor an empirical approach in which components are designed with very little analysis and tested to meet very basic design loads. Each component is developed

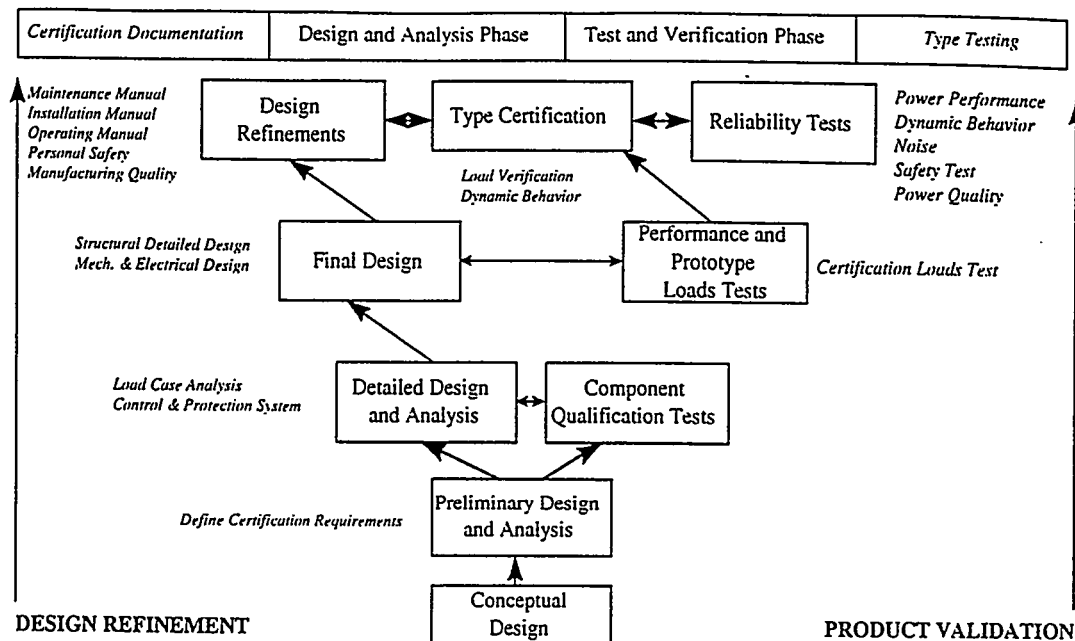


Figure 1 NREL DEVELOPMENT PROCESS

experimentally until a prototype can be built using the tested components. The prototype test results are then used to develop more complete design loads, which include dynamic loading.

Both approaches have advantages and disadvantages. Analytical tools can be used to iterate the design to an optimum configuration efficiently, before building components, and to simulate design conditions that are extremely unlikely to occur during a test program. The disadvantage of this approach is that designers are likely to miss important details, which cannot be modeled completely. The experimental approach will test all the design details but is not likely to subject the prototype to critical design limits. The best approach logically combines a balance of both analysis and testing to verify analytical models. Once a reliable set of design loads are established and the analytical model is refined, experiments can be conducted to subject a component to laboratory and field-test conditions that simulate most of the extreme static and fatigue load conditions.

Figure 1 shows the NREL "Design and Analysis Track" and the "Test and Verification Track" for product development. The combination of these two tracks presents a check-and-balance system of analytic predictions combined with test results. The Design and Analysis Track shows the stages of design starting with conceptual design and ending with verification that the original design specifications have been met. The Test and Verification Track shows how the design process is verified in stages, first component qualification tests and finally prototype reliability tests, which should lead to certification. The results from the Test and Verification Track are used to check the predictions developed in the Design and Analysis Track. As such, the iterations that occur in each of the design stages (vertically) are checked against the results of the testing stage, which are fed back into the design stages.

At the preliminary design stage, design requirements and the initial configuration are established. For all DOE/NREL funded programs, IEC 1400-1 defines the basic design requirements. NREL recommends that manufacturers meet with the certification agents to clearly define all certification requirements before the design effort begins. Preliminary analysis is done to begin to quantify the loads and economics of the wind turbine system.

At the detailed design stage, the preliminary analysis is refined by incorporating qualification test results, such as blade tests and modal tests, into a detailed dynamics analysis. The results of these analyses contribute to a loads document. This is a living document, which is used to define all design loads. It should also include all test data used to verify predicted loads. As the design evolves and changes to the

design are made, new design loads should be documented as updates to this document. A document such as this is required by all certification bodies.

At the final design stage, final analysis has occurred and resulted in complete design drawings and specifications for all aspects of the machine. Manufacturing, operation, maintenance and installation manuals should also be complete. This documentation constitutes a complete description of the design, how to build the machine, and how the machine is to be installed and operated. This collection of documentation is what the certification body will use to verify that the design complies with IEC 1400-1.

Prototype loads data collected during field tests are used to verify the predicted design loads and operational characteristics. Blade structural tests are used to verify the fatigue life and extreme load capacity of the blade (21). Performance measurements are made to verify turbine performance. Noise measurements are made to document acoustic emissions. These tests are conducted to IEC standards and constitute Type Testing requirements specified in the draft IEC certification standard. It is very important to select test sites that represent the design wind regime, extreme wind conditions and environmental conditions whenever possible.

This development process satisfies most certification requirements for a Type Certificate.

CERTIFICATION REQUIREMENTS

The proposed IEC Type Certification procedures have four basic components.

1. Design Evaluation
2. Type Testing
3. Manufacturing Quality
4. Turbine Characteristics (optional for basic Type Certificate)

Conformity statements are needed for successfully completing all the requirements of each component. When the first three component conformity statements are issued and the design loads are verified with type test data, a Type Certificate can be issued. The fourth component defines tests that quantify the turbine performance characteristics. These tests are not required to demonstrate the safety of the turbine and are therefore not required to meet basic type certification requirements, but they are usually required by customers to verify performance characteristics, which can affect the economics of their investment. In some cases, noise and power quality tests are required to meet local regulations. Figure 2 lists the requirements in each area.

The specific requirements for each element may change depending on which set of national requirements, and perhaps which certification agent, is used. The descriptions below are intended to describe general requirements for each element.

DESIGN EVALUATION

Component Tests: This optional element can be used to verify the design performance of a machine component such as a blade, gearbox, or pitch system. Component test data are most often used when the analysis of the component is difficult to accomplish with confidence. They can be used instead of an analytical approach if all the component design loads can be accurately simulated in a bench test. Usually this is impossible so the test data are used to verify specific design cases, and computer models are then used to simulate the complete set of design loads. Wind turbine blades are almost always tested for design verification

Loads Verification Document: Most design procedures for wind turbines are based on a structural dynamic model. Structural dynamic simulations are used because they can account for all the steady and unsteady aerodynamic loading, inertial loading, and control-induced loading simultaneously. It is impossible to account for all these factors with simple design calculations. However, these models can be very complicated and often require validation before the designer can use them confidently to predict fatigue and

extreme loads. Test data are commonly compared with simulations of the corresponding test conditions. This load verification process also gives the certification body confidence in the process used to develop the rest of the predicted loads. Documentation of the structural dynamic model verification has become an important part of most certification requirements.

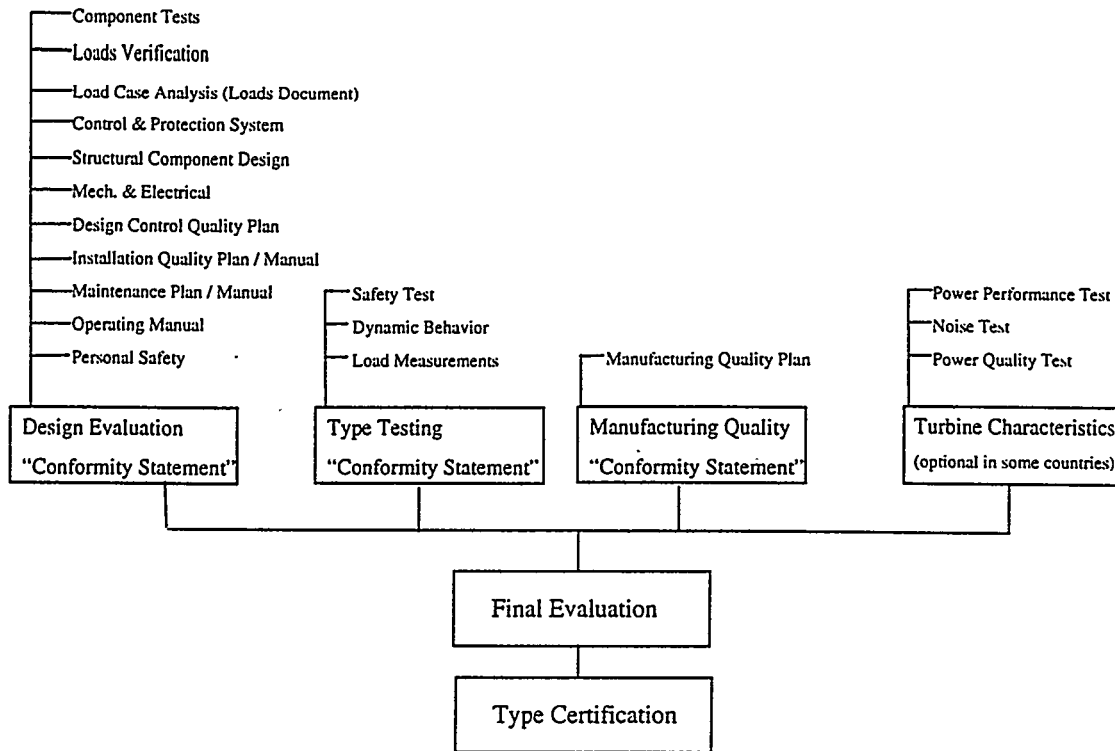


FIGURE 2. TYPICAL TYPE CERTIFICATION REQUIREMENTS

Load Case Analysis (Loads Document): A loads document should contain all the critical static and fatigue loads for plausible combinations of external conditions and operating conditions defined in IEC 1400-1. The load distributions should be determined for the blades and all critical load paths within the structure. The electrical loads, fault loads, and any control-induced loads should also be calculated for all possible operating conditions. This loads document should be a living document. It should include results from field tests that support the predicted loads. As the machine configuration changes, this document should be updated to account for any load changes. The certification body will review this document for accuracy and thoroughness.

Control & Protection System: The control and protection system should be documented in a way that clearly illustrates all possible faults and demonstrates how the protection system functions to prevent catastrophic failures. This might include control logic diagrams, fault trees, failure modes and effects analyses, test results of the control system when subjected to simulated faults, and tests of any mechanical backup systems.

Structural Component Design: The structural design of all components should be documented. Appropriate material properties should be used along with the static and fatigue loads, taken from the loads document, to evaluate structural integrity. Component tests can be used to support design calculations. If the component tests simulate all possible design loads, load distributions, static and fatigue loads throughout the life of the machine, it may be possible to substitute the component tests for analysis.

Mechanical and Electrical Design Document: Mechanical and electrical devices such as gearboxes, actuators, bearings, electrical contactors and controllers must be sized to accommodate the loads they are subjected to throughout their service life. This document must contain a translation of the general turbine loads into component loads for each of the specific devices and document the performance of the device when subjected to these loads. Analysis results or manufacturers specifications can be used to demonstrate component serviceability. For critical components, bench tests simulating the wind turbine application are recommended to demonstrate component performance. Performance and geometrical specifications are a good basis for a quality agreement between the manufacturer and the supplier and are generally required for the manufacturing quality plan. These performance and geometrical specifications should be part of this Mechanical and Electrical Design Document.

Design Control Quality Plan: The design process is the first stage of a product's life. During this stage the wind turbine will constantly change and mature. As the changes occur, design loads will be impacted, manufacturing procedures will change, and operation and maintenance procedures will change. There must be a system of controlling and documenting these changes so that the impact on other parts of the turbine design are accounted for appropriately. Such a Design Control Quality System must include Engineering Change Orders which are approved by the engineering organization, manufacturing organization, and Operation and Maintenance organization before the change is implemented. Documentation of this system is an important part of the certification review since it demonstrates the use of an engineering development process. ISO 9001 (18), section 4.4, defines a quality procedure that will satisfy a certification body's requirements for the Design Control Quality Plan.

Installation Quality Plan/Manual: A turbine is not a complete operating system when it leaves the factory floor. The machine must be installed in the field. The same machine could be installed anywhere in the world by different installation crews. Very often local building requirements may impact the final turbine configuration. To guarantee that the turbine will perform as specified in the design documentation, it must be installed to meet the original design specifications. The Installation Quality Plan/Manual must contain all specifications and procedures needed to properly install the machine.

Maintenance Manual: Many component performance predictions are based on the assumption that maintenance will be performed at specified intervals. If this maintenance is neglected or improperly done, the safety and performance of the turbine can be impacted. This maintenance will be conducted by different crews throughout the world. They will certainly be trained, but they may not be trained by the original designers. To make sure that maintenance is performed properly, a maintenance manual should describe all aspects of the required maintenance. The certification body will review these maintenance specifications to make sure that they are consistent with the design assumptions.

Operations Manual: The designers base their predicted performance on specified operating procedures. Many machines can fail if operated improperly. This manual should contain specifications for safe startup, shutdown, access to critical parts, emergency procedures, and procedures for the general control of the machine. The certification body will review the Operations Manual to assure that the operating procedures are consistent with the design assumptions and that they are clear to intended wind turbine users.

Personnel Safety Manual: The certification agent will review and evaluate the installation, operation, and maintenance manual(s) provided by the wind turbine manufacturer using applicable safety requirements/guidelines contained in the IEC 1400 series of standards.

TYPE TESTING

Safety Test: Safety tests are performed by the certification body or its authorized representative. The test is intended to demonstrate that the control and safety systems specified in the design actually do function as the designer intended. These tests include, for example, normal startup, shutdown, parking, simulated faults, and testing of the overspeed protection system. Generally the certification agent will follow a checklist documenting successful completion of each test, which verifies the design documentation.

Dynamic Behavior: Dynamic characteristics are difficult to predict. Confirmation of stable operation is very important to the safe operation of the turbine. This test can be conducted in many ways. The best way is through a well-planned loads test program that measures vibrations during the full range of operating conditions of the machine. Component and full system modal tests can also provide extremely useful data for validating dynamics models and verifying predicted dynamic characteristics. However, this may not be practical or necessary on the final production turbine if a comprehensive test program has already been conducted on a dynamically similar prototype. Dynamic similarity may be demonstrated through simple measurements on the final production machine. On small turbines, it may be possible to demonstrate dynamic stability through observation and/or long-term reliability testing. IEC standards should be used as a guide for these tests and the certification body should be consulted.

Loads Measurements: Loads measurements are a critical part of confirming the design assumptions and the dynamic load model. Normally, loads tests are conducted on a prototype, which may not match the final production configuration exactly. These loads tests need not be repeated as long as the production configuration is dynamically similar to the prototype configuration. Guidelines which describe appropriate test procedures are being developed by IEC Working Group 11. The certification agent will likely require a test report from an accredited test laboratory, which describes the results of such a test program. They will use this test report to confirm the design loads predictions before a Type Certificate is issued.

MANUFACTURING QUALITY SYSTEM

Manufacturing Quality Plan: The purpose of a manufacturing quality plan is to document a manufacturing process or set of procedures that will produce a wind turbine that meets the design specifications. This plan should include all the quality procedures for monitoring and documenting critical design specifications of components, assembly of the system, and final assembly checkout tests. ISO 9002 (19) is a good model for this plan. IEC certification standards will require that the certification body include this plan before a Type Certificate can be issued.

TURBINE CERTIFICATION

Power Performance Test: Wind turbine performance can be very difficult to predict and is crucial to the economic viability of the turbine. IEC 1400-12 specifies an internationally agreed-upon procedure for accurate methods of power performance measurements for individual grid-connected turbines. It is easier to verify the performance of a single turbine than the performance of a collection of turbines in a wind farm. Performance of small turbines operating with variable loads such as batteries are even more difficult to characterize. Standards for the latter two cases are not available. A power performance test is not required for safety reasons but is generally required to confirm predicted performance for the customer. This procedure is intended to be performed by an accredited laboratory. The certification body will require a test report from such a laboratory as part of the Type Testing documentation.

Noise Test: Noise testing is also part of the performance documentation of the machine. This test is not a safety test and is therefore optional. However, many European countries require an acoustical emissions test and compliance with a national standard for noise emissions. These tests must be conducted by an independent, accredited laboratory. IEC Working Group 5 (WG5) has developed a draft test procedure. This document will be circulated for national vote by September 1997.

Power Quality Test: In many countries, the utilities are asking for a power quality standard for wind turbines. They want a standard that addresses issues that are specific to wind turbines, such as power flicker, inrush currents, harmonic distortion and power factor. IEC WG 10 was formed to develop such a standard. This group is taking advantage of existing standards, such as IEC 1000, as much as possible. This is also considered an optional test since it is a performance-related issue.

PROPOSED PROJECT CERTIFICATION

Some experts believe Project Certification is needed to verify that the turbine is installed according to the turbine design specifications and that the site conditions are consistent with the design conditions. Others feel that Project Certification is not needed. In many cases, all components of project certification are too costly and not economically justified, especially for small turbine installations. In these cases, elements of the project certification may be selected to satisfy the customers needs. The opponents believe that this certification should not be included in the standard because it will routinely and inappropriately be requested by uninformed local governments. The working group is still debating the merits of Project Certification and has tentatively proposed the following procedure which might be appropriate for a large, multiple turbine installation.

Figure 3 describes three basic requirements for project certification: 1) project design conformity, 2) a Type Certificate, and 3) maintenance and performance surveillance.

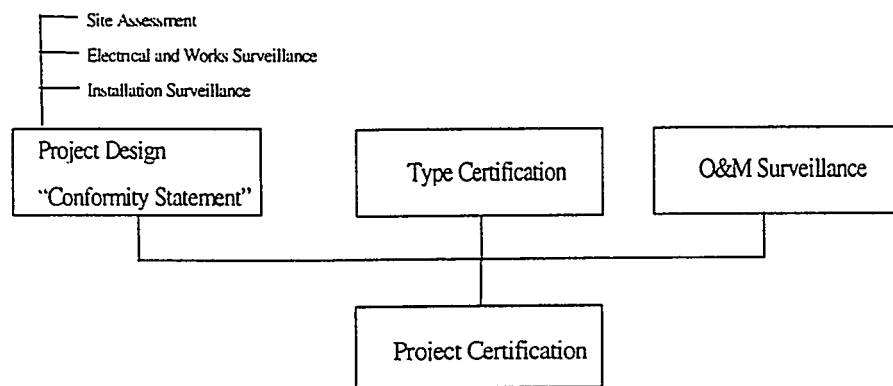


FIGURE 3. PROPOSED PROJECT CERTIFICATION REQUIREMENTS

Project Design Conformity: Much of the installation must be designed to meet local site conditions and local government requirements. Designs for the foundation must meet local soil conditions, electrical systems must interface with an existing electrical grid, and local requirements may dictate a certain tower type. These issues result in installation designs that must be performed correctly if the overall turbine installation is to operate reliably. To assure that the installation is performed according to design specifications, the installation process is reviewed and monitored (Works Surveillance). A Site Assessment is required by IEC 1400-1 to assure that the site conditions are less demanding than the turbine design conditions. This site assessment requires documentation of wind conditions through measurements such as 10-minute mean wind speed, turbulence intensity, maximum gust magnitudes, and maximum instantaneous wind shear. Wind data from wind resource assessments can be used if the data sampling rates and record averaging times are compatible with IEC 1400-12 (Power Performance Measurement Techniques). Once the turbine installation satisfies the site assessment, electrical and works surveillance, and installation surveillance, a Project Design Conformity Statement can be issued.

Type Certificate: A Type Certificate, as previously described, is required before a Project Certificate will be issued.

Operations and Maintenance Surveillance: O&M Surveillance is intended to verify that the turbine is operated within its design conditions according to the operating manual. The maintenance is monitored to assure that the turbine is maintained according to specifications defined in the maintenance manual. In order to maintain a Project Certificate, O&M Surveillance is conducted regularly throughout the life of the project. The certification body conducts unannounced audits (usually annually) to assure these procedures are being faithfully performed.

THE NREL CERTIFICATION PROGRAM

NREL has been asked by AWEA and directed by the DOE to facilitate the development of a U.S. Certification program for wind turbines. This program must result in certifications that are accepted throughout the world. According to its contract with the DOE, NREL is not authorized to issue certification but is able to perform tests and design reviews that would meet certification standards. NREL can supply these reviews to a certification agent who can use them in their certification process.

Underwriters Laboratories Inc. (UL) (22) is an international certification body operating in the United States and throughout the world. They have expressed an interest in coordinating their expertise in electrical equipment certification and manufacturing quality reviews with NREL's wind turbine design expertise to develop a certification program. Figure 4 illustrates the proposed interactions among UL, NREL, and the applicant. This certification program proposes that the applicant contract with UL for certification. UL can perform all electrical equipment reviews and manufacturing quality reviews and subcontract to NREL for design reviews of certification documents and type testing. UL anticipates using NREL reports to support its certification of the applicant's turbine. UL has field representatives located globally who could be used to perform much of the field surveillance during project certification.

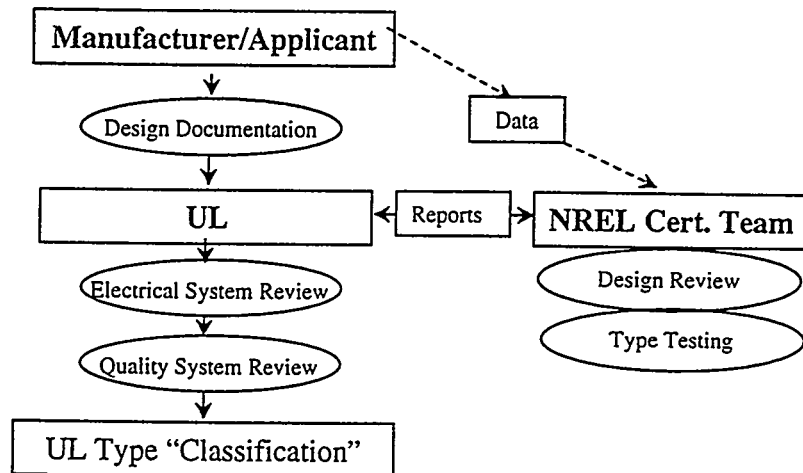


FIGURE 4. CERTIFICATION ORGANIZATION AND ROLES

INTEGRATED DEVELOPMENT/CERTIFICATION

The DOE/NREL Turbine Research program is responsible for assuring that turbines developed in the program are designed according to good engineering practice. Meeting IEC standards simultaneously satisfies both NREL's technical management responsibilities and the certification body's design conformance responsibilities. NREL requires documentation of all the important design steps. By coordinating NREL's contractually required deliverables with IEC documentation requirements, the development process becomes more efficient. NREL's design reviews are scheduled throughout the design process. Design requirements for the Turbine Research program are defined at the beginning of the program. Certification requirements will be defined at the same time. As certification documentation becomes available, NREL can perform certification reviews. If deficiencies exist, the designers will become aware of them early in the development process. This approach reduces the chances that design changes will be mandated by certification requirements that may have been poorly defined at the beginning of the design process.

The Turbine Research program requires testing of components such as the blades and of the whole prototype turbine. Generally, engineering prototypes are tested for loads and proof-of-concept testing. The design is then refined based on the test results. A production prototype is fabricated and tested for final

performance, dynamics, and reliability. These tests can satisfy Type Testing requirements if conducted by an accredited laboratory to IEC standards.

SUMMARY

Certification has become a necessity for wind turbine companies competing in the international wind turbine market. Currently, U.S. manufacturers must use European certification agents to get the required certification. NREL has integrated preparation for certification into their Turbine Research program, which facilitates the certification process. UL is interested in establishing a certification program with NREL. This program will offer the U.S. wind industry a U.S.-based alternative with world-wide authority for certification of its wind turbines.

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CURRENT PROJECTS OF THE NATIONAL WIND COORDINATING COMMITTEE

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What is the National Wind Coordinating Committee?

The National Wind Coordinating Committee (NWCC) is a multi-stakeholder collaborative formed in 1994 to support the responsible use of wind power in the United States. The NWCC's broad objectives are to provide a forum for identifying issues that impact the use of wind power, and to establish dialogue among varied stakeholder groups. The NWCC catalyzes actions determined by consensus to understand the role and value of wind energy, reduce barriers and encourage the prudent acceleration of wind power development.

NWCC's activities are designed to address:

1. Environmental and siting issues related to wind power, including avian mortality and land use considerations.
2. Wind energy transmission and utility system integration issues.
3. Opportunities within the regulatory community for self-sustaining wind generation.
4. Wind resource assessment to identify and validate promising wind regimes.
5. A sustained orderly development path for the wind industry.

The NWCC's vision is a self-sustaining commercial market for wind power – environmentally, economically, and politically sustainable.

NWCC Membership

The NWCC's broad, balanced membership is one of its key strengths. The National Wind Coordinating Committee consists of supporters of wind energy as well as those who see potential if concerns are addressed. Members provide diverse perspectives and represent the following sectors:

- Electric Utilities & Support Organizations
- Wind Equipment Suppliers and Developers
- State Utility Regulators
- State Legislatures
- Consumer Advocate Offices
- State & Federal Agencies
- Environmental Organizations
- Power Marketers

Steering Committee members and affiliations of additional NWCC members and alternates are listed below. RESOLVE, a non-profit mediation organization, provides facilitation services for the NWCC.

Current NWCC Projects

Current NWCC activities include: outreach initiatives, disseminating information about wind energy to regulators and legislators through the Wind Energy Issue Paper Series, researching distributed wind energy models, producing a wind facility permitting handbook, improving avian research, addressing transmission and resource assessment issues, and exploring sustainable development and marketing approaches.

NWCC Outreach Initiatives

As a national stakeholder organization, the NWCC seeks to partner with local stakeholders when initiating regional projects. The NWCC first holds local scoping meetings to assess its appropriate role and to confirm areas where diverse stakeholders are interested in partnering with the NWCC. The NWCC then develops tailored strategies to support market development, addresses state and regional policy issues, and implements activities. In capitalizing on “magic moments” for wind power in state policy debates, the NWCC develops concise, timely information on wind power for state policy makers, sponsors peer presentations, provides balanced expertise to new regulators, legislators and their staff, and distributes information about wind power for legislative proceedings and regulatory dockets.

In selecting focus regions for outreach, NWCC has developed a tiered approach. The NWCC’s current outreach initiatives focus on states and regions considered to be key to upcoming wind development – New England, the Upper Midwest (Iowa, Nebraska, North Dakota and South Dakota), and Texas. The NWCC is also watching for outreach opportunities in Rocky Mountain states (Colorado, New Mexico, Wyoming, Montana) and other Great Plains states (Kansas and Oklahoma), and is monitoring developments in Nevada, Washington, Oregon, Wisconsin, and Hawaii.

Regulatory & Legislative Opportunities Task Force

To assist decision-makers, the NWCC has developed a series of “Wind Energy Issue Papers” and accompanying concise “Issue Briefs” on:

- The Benefits of Wind Energy
- Wind Energy Environmental Issues
- Siting Issues for Wind Power Plants
- Wind Energy Resources
- The Effect of Wind Energy Development on State and Local Economies
- Utility Procurement of Wind Resources
- Wind in a Restructured Electric Industry
- Incorporating Wind into Resource Portfolios
- Wind Energy Transmission and Utility Integration
- Wind Performance Characteristics
- Wind Energy Costs

NWCC member organizations have distributed these publications to utility regulators, legislators, utility leaders, and other interested parties. They will soon be available to the public on the internet.

Transmission and Resource Assessment

The NWCC advises the Utility Wind Interest Group and the U.S. Department of Energy on wind resource assessment, transmission and planning issues for their Utility Wind Resource Assessment Program, Utility Value Analysis Program, and Prospective Forecasting Work. NWCC members who are knowledgeable about these issues help NWCC members to better understand resource assessment issues, and serve as conduits for related information to the full NWCC.

Distributed Wind Research Project

The NWCC has issued an RFP to solicit research on distributed wind power as a development approach. The research will explore interconnection at the distribution level, and integration with local economies, drawing upon the European co-op model. The research will examine and evaluate economic factors, policy, or industry developments behind infrastructure supporting distributed market segments in Europe, as well as the direct and indirect benefits and costs associated with distributed wind development. The NWCC will work to develop options to support distributed development in the U.S. that is both cost-competitive and beneficial to local economies.

Permitting Handbook

The NWCC Siting Subcommittee serves as a forum for the discussion of all siting issues, such as environmental impacts, permitting approaches and zoning questions. Currently, the working group is preparing a wind energy facility permitting handbook, with key contributions from states directly involved in siting wind energy facilities.

Avian Research

The NWCC Avian Subcommittee is a forum to define, discuss, and address wind-avian issues. The forum tries to involve all stakeholders connected to this issue, and focuses on public policy questions. The working group has served as an advisory group for national research on wind-avian issues. The working group has sponsored two national planning meetings to define needed research, and is in the process of planning for a third. The working group is currently authoring a guide to set research methodology standards for avian researchers and policy makers.

Sustainable Development

The NWCC has examined electric sector restructuring impacts on wind power, and evaluated options for fostering continued wind power market development. As a result of this research, the NWCC will release three reports: a review and analysis of state-level policy options to strategically promote wind energy, a scoping paper on restructuring-related system operation and transmission issues, and recommendations for wind generation under open-access transmission tariffs and restructured electric markets. The NWCC is also exploring methods to expand demand for wind power through a green power marketing project.

Key Accomplishments

The National Wind Coordinating Committee's key accomplishments include bringing focus to maintaining wind energy options for utilities in a restructured electric industry, facilitating effective management of wind-avian issues, fostering consensus and managing an ongoing collaborative process with diverse stakeholders.

For more information, including copies of NWCC publications or to join NWCC's e-mail conference, write nwcc@resolv.org or call 202-965-6398 or 888-764-WIND.

National Wind Coordinating Committee Steering Committee Members

Larry Bean, Iowa Department of Natural Resources
Matthew Brown, National Conference of State Legislatures
Ed DeMeo, Electric Power Research Institute
Steve Ellenbecker, Wyoming Public Service Commission
Peter Goldman, U.S. Department of Energy
Bill Grant, Izaak Walton League of America
Lauren Ike, Montana Power Company
Ron Lehr, National Association of Regulatory Utility Commissioners
Chuck Linderman, Edison Electric Institute
Lewis Mills, Missouri Public Counsel's Office
Robert Putnam, Utility Wind Interest Group
Randy Swisher, American Wind Energy Association
Carl Weinberg, American Wind Energy Association

Additional NWCC Members and Alternates include representatives from:

California Energy Commission	New Hampshire Consumer Advocate Office
Colorado Public Utilities Commission	Northern States Power
Conservation Law Foundation	Ohio Consumer Counsel
Enron Wind Corporation / Zond Systems	Oregon Public Utility Commission
Environmental & Energy Study Institute	PacifiCorp
Environmental Defense Fund	ReGen Technologies / AllEnergy
Green Mountain Power Corporation	Texas General Land Office
Minnesota Attorney General's Office	Texas State Energy Conservation Office
Minnesota Public Utilities Commission	Union of Concerned Scientists
National Association of State Energy Offices	Vermont Department of Public Service

REDUCING ROTOR WEIGHT

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ABSTRACT

The cost of energy for renewables has gained greater significance in recent years due to the drop in price in some competing energy sources, particularly natural gas. In pursuit of lower manufacturing costs for wind turbine systems, work was conducted to explore an innovative rotor designed to reduce weight and cost over conventional rotor systems. Trade-off studies were conducted to measure the influence of number of blades, stiffness, and manufacturing method on COE. The study showed that increasing number of blades at constant solidity significantly reduced rotor weight and that manufacturing the blades using pultrusion technology produced the lowest cost per pound. Under contracts with the National Renewable Energy Laboratory and the California Energy Commission, a 400 kW (33m diameter) turbine was designed employing this technology. The project included tests of an 80 kW (15.5m diameter) dynamically scaled rotor which demonstrated the viability of the design.

INTRODUCTION

For nearly twenty years the wind industry has struggled to be recognized as a viable energy producer. It needed to battle the new-industry woes of being taken seriously by the nation's utilities and being accepted by the public. In addition, it was dealing with an energy source, the wind, which was not understood, and at the same time attempting to develop hardware having no operating history. There were so many new challenges during the early years of the industry that thoughts of innovative rotor systems could not be considered seriously. The design mentality was to avoid rotor problems by taking an ultra conservative approach, build it rigid. Also, during the tax-credit days cost was not a great concern since the systems were sold as a 100% tax credit to investors, making high prices actually attractive to many. Therefore, there was no serious effort or interest to reduce system costs.

Now the picture has changed. After fifteen years of operating experience with many mechanical failures and technical errors, a greater knowledge and respect for the wind, and no tax credits to sweeten the economics, the industry is now faced with the task of competing in the real world against large established energy producers. In this market, as with most, the bottom line is cost and reliability. In the past five years the industry has made major strides in developing reliable products. It is time now to make strides in reducing costs.

There are four major components that make up a wind turbine: the support (or tower), the power train and brake, the controller, and the rotor. Except for the controller, the costs of these components are generally proportional to weight. The subject of the research reported here concerns an innovative rotor design which has achieved a major reduction in weight, and cost, compared to conventional wind turbine rotors.

This work was supported by contracts with the National Renewable Energy Laboratory and the California Energy Commission.

THE “STANDARD ROTOR”

Wind turbine rotor performance is primarily a function of disk area, blade area, pitch, and tip speed. Parameters having a lesser effect on performance are airfoil shape, twist, taper, and number of blades. If the design approach is a conservative one, and rigidity is desired, large root structure is required to support bending moments and the outboard structure is generally tapered to reduce the aerodynamic loads that produce those moments. An added benefit to this planform is the improved aerodynamics it produces. The variable chord distribution helps produce a more uniform induced velocity through the disk which improves efficiency. The resulting structure is very rigid and experiences very small elastic deflections, even in the highest of winds. Due to the high blade area in the inner half of the disk needed to support the air loads, not many blades are required to meet the total blade area necessary to achieve the desired performance. This is usually two or three. This defines the “standard rotor”.

The “standard rotor” design fails to capitalize on a powerful ingredient of rotating systems which can help support the high aerodynamic bending moments which now must be resisted 100% by the structure. That is the centrifugal force field. Allowing the structure to deflect out of plane immediately employs a centrifugal force that counteracts the aerodynamic force that caused the deflection. The two forces stabilize at a modest deflected position of the blade. The centrifugal forces are an order of magnitude greater than the air forces and therefore only small deflections are required to produce the centrifugal force component necessary. It is this phenomenon that serves as the basis for the innovative rotor design discussed herein.

TAKING ADVANTAGE OF THE SQUARE LAW

Remembering that one of the parameters that most influences performance is blade area, one would initially think from the cost standpoint that it would make sense to use the fewest number of blades possible to achieve the necessary area. This has some validity when complex blade geometry is being fabricated which requires a great deal of setup time and when the hand lay-up time does not increase significantly with blade chord. The blade cost is driven more by labor expense than material expense. Even single blade turbines have been constructed, however the standard in the industry is three. There is a significant weight penalty when increasing chord to increase blade area because, when maintaining constant airfoil and skin thickness ratios, the weight goes up as the square of chord. Had the area been achieved by adding another blade the weight would have increased linearly. For example doubling the chord would quadruple the weight whereas adding another blade would only double it.

Of course the square law also works in reverse. By reducing the chord by a factor of one half, the weight is reduced by a factor of one forth. This is depicted in a simplistic way in *Figure 1* where an airfoil is shown having a rectangular cross section. The cross sections of a 2-bladed rotor are shown on the top with chord “c” and thickness “t”. The running weight of each blade would be tcp where p is the material density. The total weight would be $2tcp$. Shown on the bottom are the cross sections of a 4-bladed rotor having the same total aerodynamic blade area with the airfoils having the same thickness ratio, t/c , and material density. It is easily seen that each blade weight would be one-fourth of that of the 2-bladed rotor and that the total weight would be one half. This comparison was made for blades with solid cross sections, but it would also be true for hollow blades with skin, assuming the ratio of skin thickness to chord was maintained. In the limit as the number of blades increases with chord dropping proportionally, the rotor weight would approach zero. This is shown in *Figure 2* where total rotor weight (blades only) for a 400 kW size turbine is plotted against number of blades. A downward trend is maintained for any number of blades, however the principal benefits are at the low end.

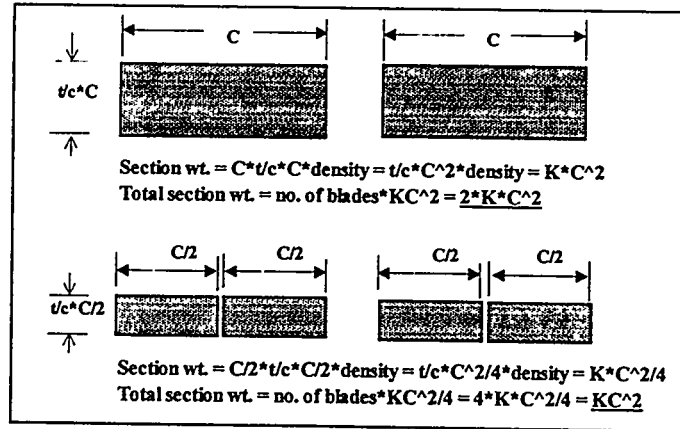


FIGURE 1. THE EFFECT OF THE SQUARE LAW ON BLADE WEIGHT

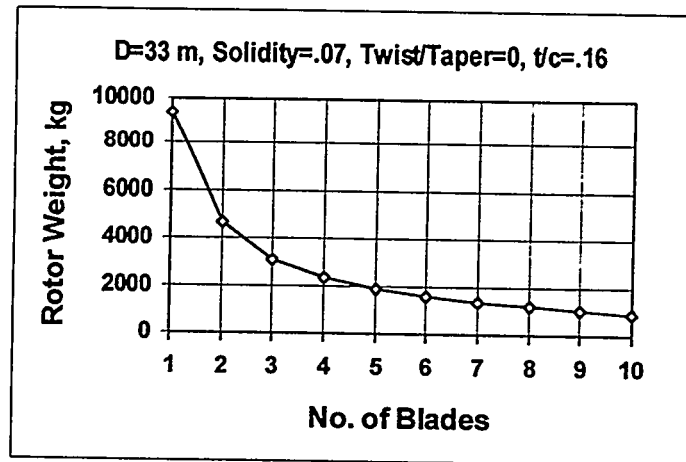


FIGURE 2. ROTOR WEIGHT VS. NUMBER OF BLADES

The weight benefits of increasing the number of blades are significant, however in the real world they are not as impressive as one might infer from *Figure 2*. There are two 'real world' issues that were not addressed above. The first is static stress. Very often the wind condition that dictates rotor design is the hurricane wind with the rotor stopped. The increased flexibility of the blades which occurs as number of blades increase and chord decreases benefits this design condition in that the blades, in their highly deflected state, present a reduced planform to the wind. This reduces the total blade drag as well as its moment arm. The static deflection of a 16.5 meter flexible blade in a 62 m/s wind is shown in *Figure 3*, and, for comparison, a typical stiff tapered blade deflection is also shown. The effects of deflection reduce the skin stress at the blade root, however they are not enough to offset the increased stress created by the much reduced blade cross-section moment of inertia. To bring the stress back to acceptable levels the skin thickness must be increased which compromises to some degree the weight reduction. This is demonstrated in *Figure 4*, which compares weight and stress of 3-bladed and 5-bladed untapered rotors. These results are

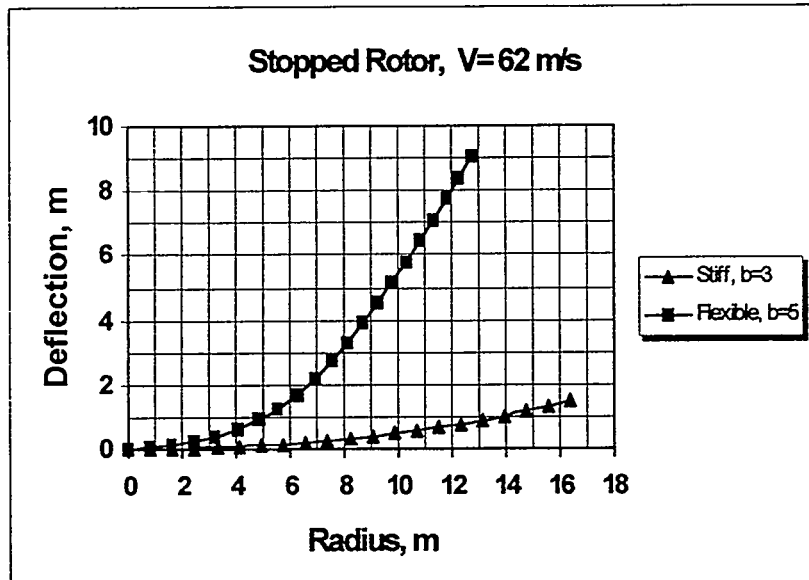


FIGURE 3. BLADE STATIC DEFLECTION

shown for a 33 meter rotor with a solidity of 7 % ($\sigma = .07$). The airfoil is an NREL S813 section consisting of a uniform skin with three internal foam-filled cells. Blade root stress and total rotor weight (not including hub) are plotted against section skin thickness. The design condition is a locked rotor at a wind speed of 62 m/s (138 mph). Selecting a limit stress of 30,000 psi indicates the 3-bladed rotor would require a skin thickness of at least 0.57% of the chord and the 5-bladed rotor at least 0.85%. The rotor weights corresponding to these points are 3350 kg (7385 lbs) and 2650 kg (5840 lbs), respectively. This represents a 21% reduction in weight for the 5-bladed rotor compared to 40% using the square law directly, without consideration for stress as in *Figure 2*.

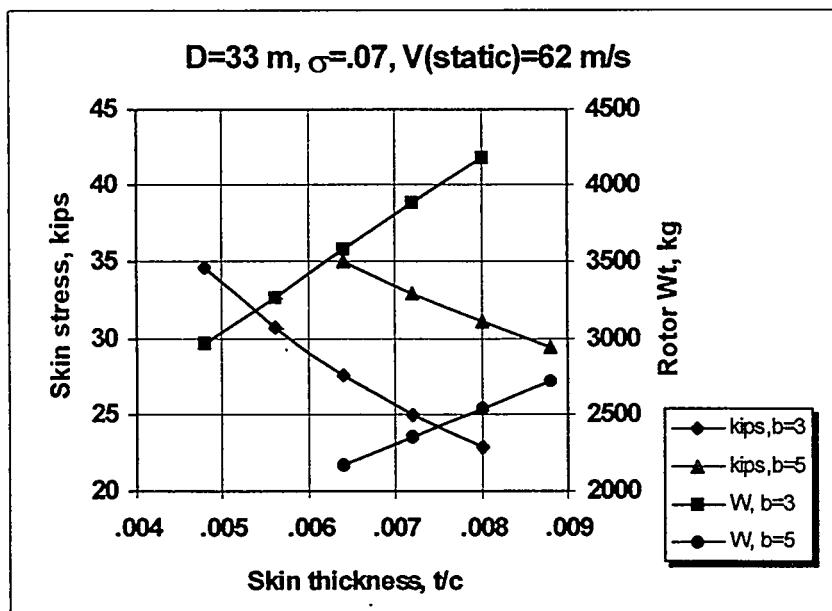


FIGURE 4. EFFECT OF SKIN THICKNESS ON STRESS AND WEIGHT

The second 'real world' issue is the phenomenon of stall flutter. When increasing the number of blades, but retaining the same blade area, chord decreases and blade aspect ratio increases. Assuming the same material properties and section thickness ratio, the higher aspect ratio produces a lower torsional frequency. Torsional frequency is proportional to the square root of GJ divided by the polar moment of inertia, where G is shear modulus and J the area moment of inertia, and J is proportional to the forth power of chord whereas mass moment of inertia to only the square of chord.

Stall flutter can occur in propeller, gas turbine, helicopter, and wind turbine blades when the fluctuations in the near wake of the stalled airfoil coalesce with the torsional natural frequency. Energy can be fed into the blade resulting in a torsional instability. It is an instability where the flatwise and edgewise modes do not participate. If a wind turbine blade is not allowed to slow down after the onset of stall flutter, i.e. the controller causes it to motor, the angular deflections can diverge resulting in structural failure. To avoid stall flutter the blade torsional frequency must be sufficiently above the excitation frequency in stall. Although the phenomenon is elusive and difficult to understand, a design criterion has been developed in the helicopter industry where the instability was found to be related to the tip speed, chord, and torsional frequency. The term "reduced velocity" (RV) was coined which is the ratio of velocity (tip speed) to the product of the half chord and the blade first mode torsional frequency. Normally the blade velocity at the 3/4 radius is used and thus reduced velocity is defined as:

$$RV = (.75) \cdot \Omega R / (.5C \cdot \omega)$$

where ΩR is tip speed, C is chord, and ω is torsional frequency. It has been observed that this phenomenon is also effected to the extent that the angle of attack has exceeded the initial stall angle making it difficult to establish a specific RV design criterion. Researchers have suggested, as a rule of thumb, to use a value of 1.5. In other words, stall flutter in general can be avoided if the reduced velocity is kept to 1.5 or lower. It is this criterion that limits number of blades and aspect ratio. *Figure 5* shows reduced velocity and chord versus number of blades for a 33 meter rotor with a solidity of 7%, and indicates that the maximum number of blades would be five for a rotor with this tip speed and solidity.

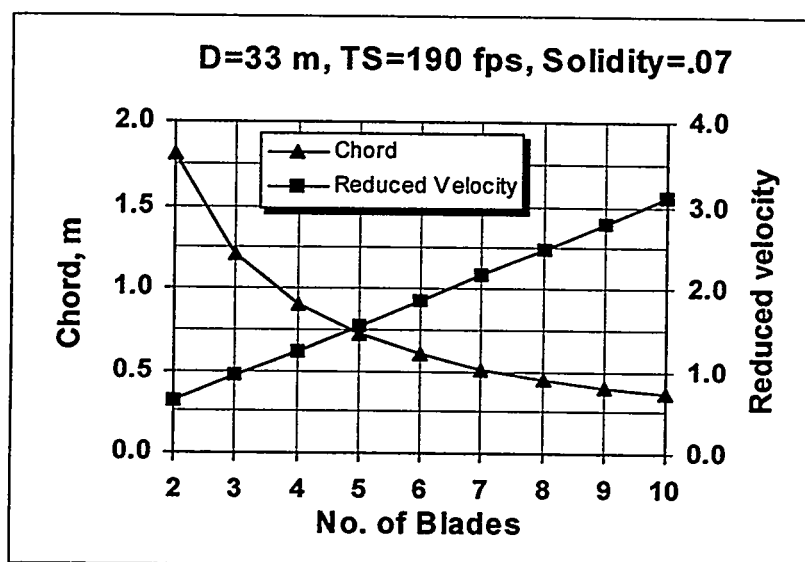


FIGURE 5. VARIATION OF CHORD AND RV WITH NO. OF BLADES

EFFECTS OF TWIST AND TAPER

Unfortunately using pultrusion to fabricate the blades precludes the ability to incorporate twist and taper and the aerodynamic benefits they provide. The weight benefits of increasing the number of blades applies to twisted tapered as well as straight blades; however the purpose of this research was really to reduce rotor cost, not simply weight as indicated in the title, and it will be shown that the labor costs of fabricating tapered blades offsets the performance benefits. The following discussion compares the performance and costs of the two blade types.

The PROP93 computer code was used to compare the performance of the two rotors. The C_p curves for the 5-bladed rotor with and without taper and twist are shown in *Figure 6*. The tapered blade used a maximum to minimum chord ratio of about 6 to 1, and was twisted a total of 21 degrees. Variable airfoil sections were used for the tapered blade to optimize the aerodynamics, and chord and pitch of the tapered blade were adjusted to produce the same maximum power as the untapered blade. It is clear that twist and taper improves performance, which is also demonstrated in the annual energy production shown in *Figure 7*.

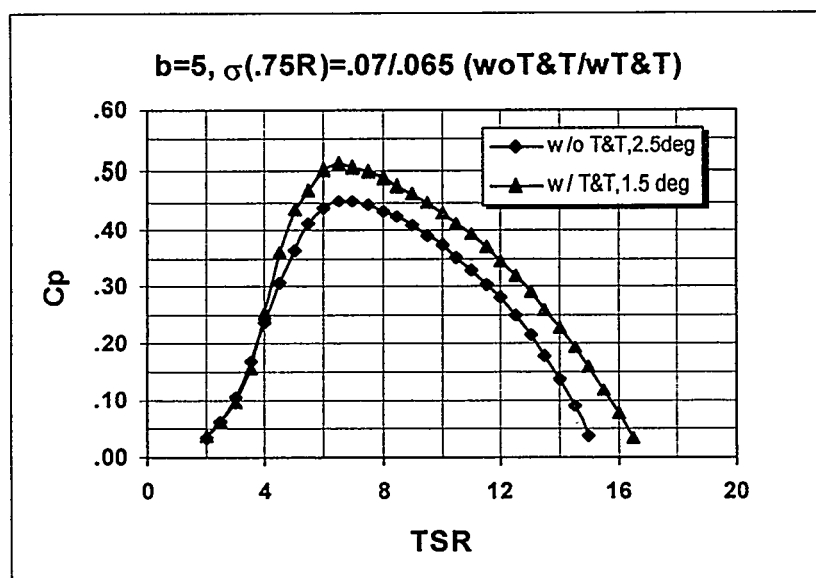


FIGURE 6. EFFECT OF TWIST AND TAPER ON C_p

The improvement in annual energy capture ranges from 7% at high winds to 16% at low winds. The more significant comparison, however, is that showing cost of energy of the two rotor types. The rotor capital costs must first be estimated. Costs were developed based on component weights and the cost per pound to fabricate. The rotor weight for the 5-bladed untapered blade was presented in *Figure 4*. The weights (section dimensions) for the tapered/twisted blade were calculated using the same design criterion that the maximum stress for the stopped rotor be held to 30,000 psi, and the chord distribution used to generate the C_p curve in *Figure 6* was used. *Table 1* lists the various weights and costs of the primary rotor components. The cost per kilogram (kg) of the untapered blade of \$6.61 (\$3/lb) was obtained directly from a pultruded blade supplier. The additional costs shown are for root doublers (stiffeners) which are required to increase the section inertia over the high moment region. These can be pultruded parts but require an additional step to bond them to the blade, and thus the cost is increased slightly to \$8.82/kg (\$4/lb). A low

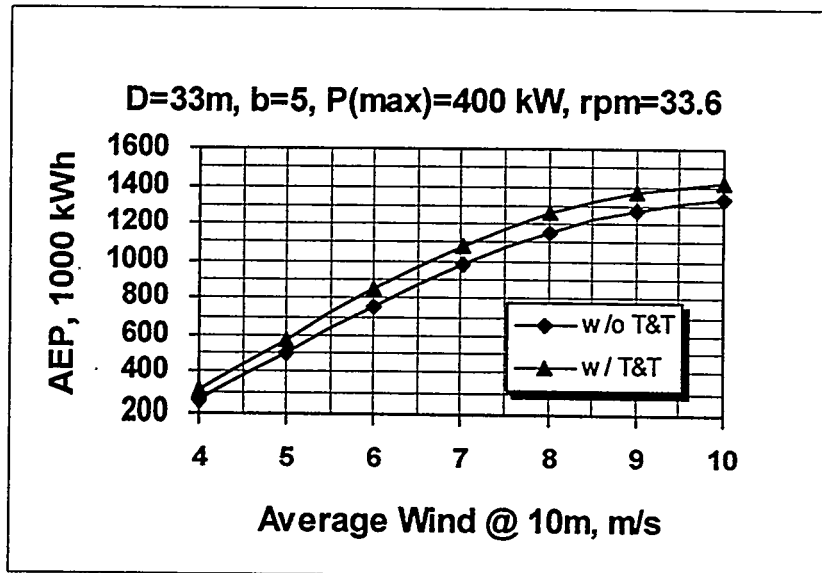


FIGURE 7. EFFECT OF TWIST AND TAPER ON AEP

TABLE 1. WEIGHT AND COST COMPARISON OF ROTOR TYPES

(D = 33m)	Wt, kg	\$/kg	\$/blade	\$/rotor
UNTWISTED/UNTAPERED - FIVE BLADES				
Blade	326.9	\$ 6.61	\$ 2,161	\$ 10,804
Doublers	78.8	\$ 8.82	\$ 695.33	\$ 3,477
I.e. ballast	89.5	\$ 4.41	\$ 394.87	\$ 1,974
Filler	30.6	\$ 13.23	\$ 405.08	\$ 2,025
Total Blade	525.9			\$ 18,281
Hub(45%)	1183.3	\$ 2.20		\$ 2,603
Total	3812.8		\$ 3,656	\$ 20,884
TWISTED/TAPERED - FIVE BLADES				
Blade	271.4	\$ 13.23	\$ 3,590	\$ 17,952
I.e. ballast	49.2	\$ 4.41	\$ 216.84	\$ 1,084
Filler	83.5	\$ 13.23	\$ 1,104	\$ 5,521
Total Blade	404.0			\$ 24,558
Hub(45%)	909.0	\$ 2.20		\$ 2,000
Total	2929.2		\$ 4,912	\$ 26,558
TWISTED/TAPERED - THREE BLADES/STIFF				
Blade	2008.3	\$ 13.23	\$ 26,570	\$ 79,709
Hub(45%)	2711.0	\$ 2.20		\$ 5,964
Total	8735.9		\$ 26,570	\$ 85,674

cost ballast is added behind the leading edge to move the chordwise center of gravity forward, and a lightweight filler (foam) is injected to stabilize the skin. Finally, the hub is added which, from a survey of many systems, is estimated to weigh 45% of the total blade weight. It was assumed the tapered blade is fabricated using hand laid-up procedures at a cost of \$13.32/kg (\$6/lb). The leading edge ballast was installed only over the outboard half of the blade to guard against classical flutter where the torsional

stiffness is low. Greater filler weight is required due to the higher inboard chord and thickness of the tapered blade. Included in *Table 1* is the cost of a typical 3-bladed stiff rotor. Its weight was taken from *Figure 8* where several existing rotor system weights are plotted versus diameter. For a 33m rotor a value of 140 kg/m² was used which includes the hub weight.

The weight and cost information given above, along with the energy capture of *Figure 6*, were used to compute the cost of energy (COE) for the rotor assembly. To be consistent with conventional COE calculations for complete systems, a fixed charge rate of 10.2% (NREL default value) was applied to the rotor costs in *Table 1*. The results are plotted against mean wind speed in *Figure 9*. The flexible 5-bladed rotor shows a clear COE advantage over the more conventional 3-bladed stiff rotor (0.0032 \$/kWh versus 0.011 \$/kWh at 6 m/s). It is also interesting to note that the twisted tapered blade has about the same COE as the pultruded blade assuming its fabrication cost of \$13.32/kg (\$6/lb). Obviously any reduction in these costs would result in the tapered blade having the lower COE.

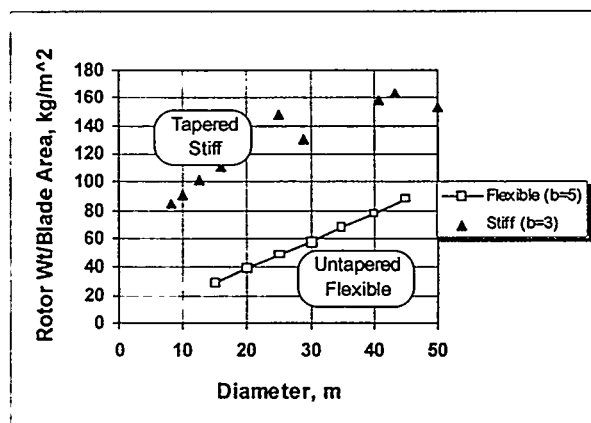


FIGURE 8. WEIGHT COMPARISON

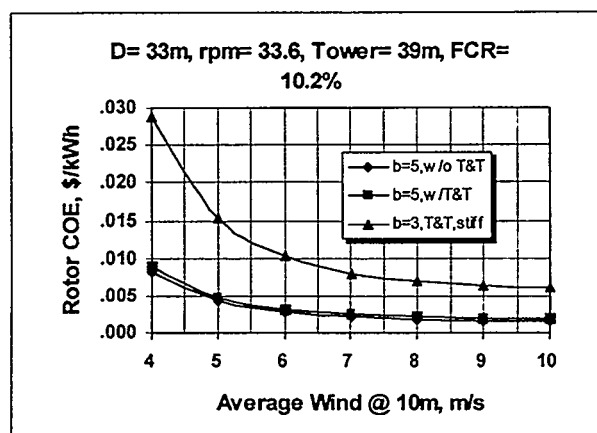


FIGURE 9. ROTOR COE COMPARISON

FIELD TESTS OF FLEXIBLE ROTOR

The NREL contract included the fabrication and test of a 5-bladed flexible rotor utilizing pultruded blades. The 400 kW design with a diameter of 33m was scaled down to an 85 kW size which resulted in a rotor diameter of 15.5m (51 ft) and blade chord of 0.34m (13.5 in). All non-dimensional blade frequencies of the 400 kW design were maintained for the scaled down version so that blade stability characteristics could be simulated. The rotor was mounted on an available main frame and tower and installed at a site in the San Geronio Pass in Palm Springs, CA. The rotor incorporated a new spoiler-flap device for overspeed control. The purpose of the test was to demonstrate the basic stability of the rotor and to measure rotor performance and blade loads to compare with theory. The validation of the computer codes was necessary to provide the confidence to use these tools to complete the design of the utility-scale 400 kW rotor.

The analysis of the test data is continuing at the writing of this paper, however preliminary results show good correlation of blade bending moment data with an aeroelastic code developed by PSE for flexible wind turbine rotors. The code is called FLEXDYNE, and it simulates the first five fully coupled modes of the flatwise, edgewise, and torsion degrees of freedom. The turbine yaw degree of freedom is included, and wind gusts and turbulence can also be simulated. Additional features include tower shadow and tip brake

aerodynamics. The program was written in a spreadsheet format (e.g. EXCEL or Lotus 123), and using Lotus 123 (Release 5), each revolution takes about 25 seconds on a 166MHz computer.

The test rotor was gaged to measure blade flat, edge, and torsion moments, and spoiler-flap position and loads. The prevailing wind during the test was from the west however there was a high level of north-south unsteadiness that was detected by the sonic anemometer. The amplitude and frequency of the crossflow were sufficient to excite certain blade natural frequencies which were not present in the initial FLEXDYNE results. Only after the crossflow was simulated did the responses reveal the higher frequencies. Sample time histories for five revolutions are shown in *Figures 10 and 11*. The data recording system used for the test

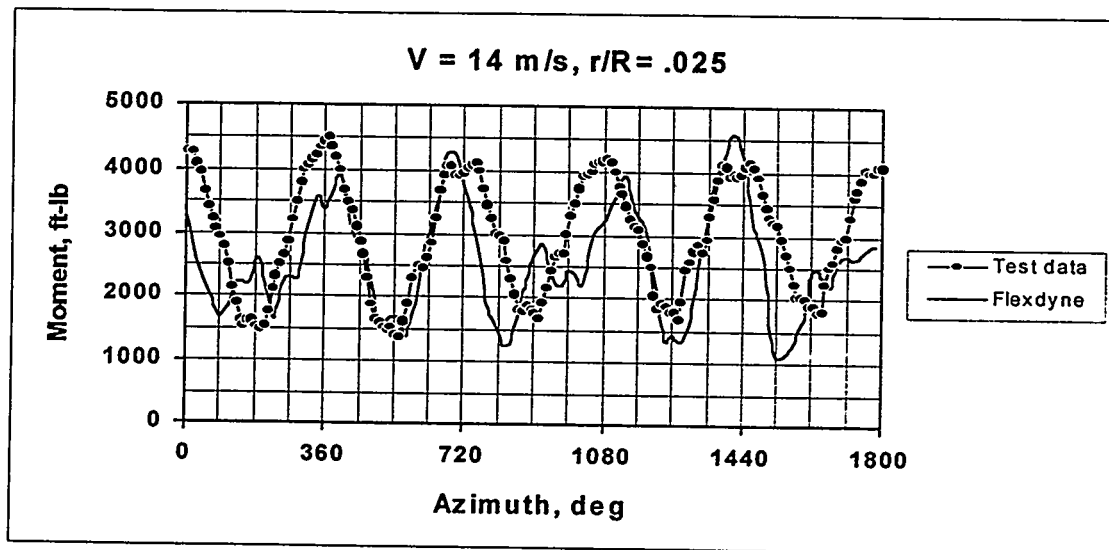


FIGURE 10. FLATWISE MOMENT

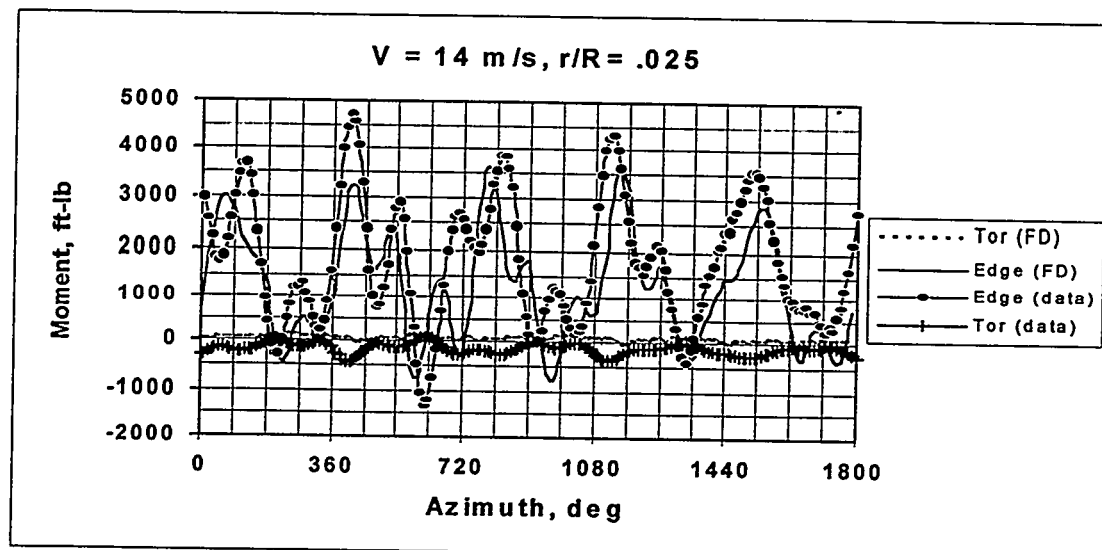


FIGURE 11. EDGEWISE AND TORSION MOMENTS

was the NREL ADAS system. Flatwise and edgewise moments demonstrate good correlation with FLEXDYNE both in their steady level as well as peak to peak. The higher frequency content, which are natural frequency transients due to the flow unsteadiness, also appear in the FD simulation. Although the torsional moments are low relative to flat and edge, there are clear differences between the measured and predicted moments which cannot be explained at this early stage in the data analysis.

CONCLUSIONS

It has been shown that increasing the number of blades of wind turbine rotors without increasing total blade area substantially reduces total rotor weight. This occurs because blade weight decreases as the square of chord when the section dimensions are reduced proportionally. As a result of this, blade aspect ratio increases, and with it an increase in blade flexibility. Flexibility introduces potential structural and aeroelastic problems which must be addressed in the blade design. The root structure must be stiffened in the flatwise direction to reduced stresses and the blade torsional natural frequency must be maintained above a certain level to avoid stall flutter. These design criteria place upper limits on the number of blades.

Weight and cost comparisons of a pultruded rotor with a conventional 3-bladed stiff rotor demonstrated significant advantages of the flexible blade design. Rotor weights of less than one-half of those of stiff systems appear achievable with manufacturing costs less than one-third. The cost comparison assumed pultruded blade cost at \$6.61/kg (\$3/lb) and tapered blades at \$13.23/kg (\$6/lb). Tapered/twisted blades are shown to improve energy capture about 13% over straight untwisted blades for a rotor with the same diameter and rating; however the rotor-system cost of energy of the flexible rotor, due to its reduced weight and manufacturing cost, is about one-third that of the stiff system (.0028 vs .0103 \$/kWh at 6 m/s). A flexible rotor incorporating twist and taper demonstrates a weight savings of over 20% compared to the pultruded blade, and when factoring in its improved performance, achieves essentially the same COE.

Field tests of a flexible pultruded rotor scaled down from a 400 kW design demonstrated the viability of the flexible rotor concept. Blade loads agreed well with predicted values and no evidence of rotor or blade instabilities were found. A company-developed aeroelastic analysis (FLEXDYNE) was used to predict rotor behavior and blade loads, and good correlation with the measured loads has been demonstrated.

SITE-OPTIMIZATION OF WIND TURBINE GENERATORS

BY

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AUSTIN, TEXAS**

ABSTRACT:

The Danish Company Nordtank is one of the pioneers within the wind turbine industry. Since 1981 Nordtank has installed worldwide more than 2500 wind turbine generators with a total name plate capacity that is exceeding 450 MW.

The opening up of new and widely divergent markets has demanded an extremely flexible approach towards wind turbine construction. The Nordtank product range has expanded considerable in recent years, with the main objective to develop wind energy conversion machines that can run profitable in any given case.

This paper will describe site optimization of Nordtank wind turbines. Nordtank has developed a flexible design concept for its WTGs in the 500/750 kW range, in order to offer the optimal WTG solution for any given site and wind regime; Through this flexible design, the 500/750 turbine line can adjust the rotor diameter, tower height and many other components to optimally fit the turbine each specific project. This design philosophy will be illustrated with some case histories of recently completed projects.

I. INTRODUCTION

The Danish Company NEG is one of the pioneers in the global wind energy industry. Since 1981 NEG has installed worldwide more than 2500 wind turbine generators (total nameplate capacity > 450 MW), including 1286 units (total nameplate capacity 101 MW) in North America.

NEG offers state-of-the-art wind energy conversion technology that is optimized for specific wind and site conditions. NEG currently offers wind turbine generators ("WTGs") with nameplate capacities that range from 150 kW to 1.5 MW. NEG's wind turbines have shown excellent performance and are supported by reliable warranties. All NEG's WTGs are certified by the major independent and reputable testing agencies.

NEG's design philosophy is characterized by simple, well-proven concepts, emphasizing performance and durability. All the components of the NEG WTGs are robustly designed; enabling the machine to absorb and handle the peak loads it is exposed to. Value engineering and innovation are important criteria within NEG's R&D effort, but primary emphasis is placed on the long-term durability and performance of each WTG.

During the last four years NEG's wind turbines in the 500/750 kW range have emerged as the most efficient wind turbines presently available on the market. Through flexible design, the 500/750 kW turbine line can adjust the rotor diameter, tower height and many other components to optimally fit the turbine each specific site, wind regime and climatic conditions. To date, NEG has installed more than 400 NTK 500/750 kW WTGs worldwide in a wide range of wind regimes and site conditions.

In September 1995 NEG was the first company to install a commercial MW+ wind turbine. The experience from the operations of this and other 1.5 MW WTGs in combination with continuous further technical development has given NEG a leading role for the supply of MW+ wind turbines: this fall NEG will install in Germany the first wind power plant (18 MW) utilizing only 1.5 MW WTGs. Recently NEG's 1.5 MW wind turbine won the prestigious German Industry Forum Design Award.

This paper will discuss above-mentioned site optimization of Nordtank wind turbines in detail. First we will give you an overview of the design parameters for wind turbines. Subsequently, we will outline Nordtank's flexible design concept: site-optimization of Nordtank wind turbines. Finally, this design philosophy will be illustrated with some case histories of recently completed projects.

II. Design Parameters for Wind Turbines

In the following you will find an overview of the site (country) specific parameters that affect the wind turbine choice and/or design:

- * Wind Regime:
 - Mean Wind Speed;
 - Annual Wind Speed Frequency Distribution;
 - Turbulence;
 - Shear Factor;
 - Exposure to extreme wind speeds;
 - Air Density.
- * Climate conditions:
 - Monthly Mean Temperatures;
 - Extreme Temperatures;
 - Exposure to environmental conditions, such as:
 - + Lightning;
 - + Icing;
 - + Special Atmospheric Conditions, such as maritime, dust, etc.
- * Site conditions / infrastructure:
 - Site Accessibility;
 - Terrain Conditions.
 - Availability of sites / Available Infrastructure;
- * Power Quality
 - Specific grid requirements;
 - Isolated or Independent Grid.
- * Permitting:
 - Permitting Requirements;
 - Visual impact;
 - Noise.
- * Economical Factors
 - Project economics evaluated on kW or kWh basis;
 - Possible grants or incentives that are tied to the name plate capacity;

The opening up of new and widely divergent markets is causing that the range of above-mentioned design parameters is expanding. It is impossible to develop an all-round wind turbine that will perform optimally in all wide ranges of above-mentioned parameters. For example: the windy mountain ridges in Southern California require a different wind turbine than the plains in the Midwest; The cold and windy plains in Inner Mongolia demand a different WTG design than the moderate wind resource in India; The extreme coldness in Northern Scandinavia requires different design features than the windy mountain ridges in Spain.

The current wind energy markets demand an extremely flexible approach towards wind turbine design and construction. The Nordtank product range has expanded considerable in recent years, with the main objective to develop wind energy conversion machines that can run profitable in any given case.

III. SITE OPTIMIZATION OF THE NORDTANK WIND TURBINES

In order to meet the wide range of demands from the various project sites (and countries), Nordtank has developed for its wind turbines in the 500/750 kW range, a site-customizing concept that will result in the optimal solution for any given situation. Through flexible design, the 500/750 turbine line can adjust the main WTG components to optimally fit the turbine each specific site, wind regime and climatic conditions. To date, Nordtank has installed more than 400 NTK 500/750 kW wind turbine generators worldwide in a wide range of wind regimes and site conditions.

The following components of the Nordtank turbines in the 500 - 750 kW range can be adapted to the specific project requirements:

- * Rotor Diameter:
Nordtank's WTGs in the 500-750 kW range can be equipped with either a 37m, 41m or a 43m rotor. Larger rotor diameters up to 50 meters are currently under development and testing.
- * Tower Design:
Nordtank's 500/750 kW WTGs can utilize various tower designs, which will result in hub heights ranging from 35m up to 60m. As a standard Nordtank recommends tubular towers for durability and safety reasons. As an option Nordtank has lattice tower designs available for its wind turbines in low to moderate wind regimes.
- * Fixed Pitch Setting of the blades:
Based upon the actual air density at the site, Nordtank will pitch the blades upon installation, in order to compensate for air density. In this way Nordtank will minimize potential losses due to reduced air density. The turbulence intensity at the site has also influence on the pitch setting of the blades.
- * Type of Generator:
The name plate rating of the turbine depends on the wind resource, air density, terrain conditions, pitch setting of the blades and project requirements. In addition to generators with various name plate ratings, Nordtank's WTGs in the 500/750 kW range can be equipped as an option with dual wound generators, which give the turbine a lower name plate rating at lower wind speeds and increased efficiency. This option is economically attractive in relatively low wind regimes.
- * Drive Train:
Rating and rotational speed depending on the load spectrum of the wind resource. The load spectrum is determined by the wind speed distribution, turbulence intensity, exposure to extreme wind speed and air density.
- * Power Conditioning Equipment:
As a standard Nordtank wind turbines are equipped with partial phase compensation, which is resulting in a power factor close to unity. If required, Nordtank's wind turbines can be equipped with full power factor correction equipment, in order to meet and/or exceed the applicable IEEE standards. In addition, Nordtank can incorporate additional features into its wind turbine controllers or SCADA system, in order to meet the requirements of the specific grid conditions.

- * **Special Climate Protection Package:**
 Nordtank has designed and offers optional modifications for extreme climate and environmental conditions, including:
 - + **Cold-weather Package**, that can include the following features: Special grades of steel for the structural components in the nacelle and the tower; Heaters for the anemometer, wind vane, generator, gear reducer, slip rings and controller. The wind turbine controller will be specially outfitted for operations in cold weather conditions; The cut-out wind speed and temperature can be customized for the site conditions and can be brought down to -30 Degrees Celsius (-22 Fahrenheit).
 - + **Hot-weather Package**, that can include the following features: Extra Cooling Equipment for the generator, gear reducer and controller. The wind turbine controller will be specially outfitted for operations in hot weather conditions; Special lubricants will be utilized.
 - + **Lightning Protection System**: As a standard Nordtank wind turbines include a complete lightning protection system for the nacelle compartment, tower and controller. As the nacelle section is constructed as a "cage of Faraday", it gives an excellent natural protection against lightning. The lightning ground path specifically avoids all electronics and mechanical equipment within the nacelle and the tower. In areas with exposure to frequent and intensive lightning a lightning protection system for the rotor is recommended as well: Lightning strikes on the blades will be captured by an integral metallic receptor in the blade tip and diverted by a conduction system through the blade and hub to the tower wall and safely to the ground.
 - + **Extra corrosion protection package against Aggressive Atmospheric Conditions (Maritime situation)**

Nordtank currently offers the following configurations of turbines in the 500-750 kW range:

- * NTK 500/37H
- * NTK 500/37
- * NTK 500/41
- * NTK 550/41
- * NTK 600/37
- * NTK 600/37H
- * NTK 600/41
- * NTK 600/43
- * NTK 600/180/43
- * NTK 750/43
- * (NTK 750/44)
- * (NTK 750/48)

note: the WTGs are identified by their nameplate capacity / rotor diameter; H indicates that the WTG has been outfitted for an extremely high energetic wind resources.

IV. CASE HISTORIES

In the following you will find case histories that will illustrate Nordtank's optimal solution concept for its wind turbines in the 500-750 kW range:

a. Nordtank WTGs in moderate wind regimes.

NUON Near-shore Wind Power Plant, Flevoland - the Netherlands:

Host Utility:	NUON
Owner and operator:	NUON, contact: Mrs. Annemarie Goedmakers, Director - Renewable Energy. Postbus 9039, 6800 EZ Arnhem, the Netherlands, tel. (31)263772143, fax (31)263772081
Nameplate Capacity:	17.4 MW
WTG Configuration:	29 NTK 600/43 WTGs
Years of Operation:	In operation since middle 1996.
Availability:	> 98.5% (Hour of Operation > 100,000 hours). Cumulative Production: > 15,000 MWh.
Nordtank's responsibility:	EPC contract, Five Year O&M, Service Contract
Characteristics of the site optimization:	Nameplate Capacity 600 kW; Largest available rotor, 43 meter; Relative high tower, 48.8 m, resulting hub height 50 meter; Positive pitch setting due to low turbulence intensity; Extra corrosion package due to offshore location.

b. Nordtank WTGs in high energetic wind regimes.

More than 125 Nordtank wind turbines have been installed in highly energetic wind regimes (mean wind speed > 10 m/s). The installation and operation of these wind turbine have given Nordtank the base for effectively optimizing its wind turbines for the extreme forces from the environment.

For our specific experience in high energetic wind regimes Nordtank would like to highlight one wind power plant in Northern Ireland that is exposed to a highly energetic wind resource. The combination of high air density, cold temperatures, high turbulence and a mean wind speed above 10 meters per second is resulting in an unmatched, extreme load spectrum. The Nordtank 500/600 kW turbines at these sites operate more than 20% of the operating time in the stall-phase of their power curves. The high availabilities of these machines is the evidence of the robustness of the of the design of the 500/600 kW WTG.

Corkey wind power Plant, Ireland:

Host Utility:	Northern Ireland Electric
Current owner and operator:	Scottish Power, U.K. Contact: Mr. Steven Cowey, Scottish Power, Generation Wholesale Division Cathcart House, Spean Street, Glasgow U.K. tel. (44)41-6377177
Nameplate Capacity:	5 MW.
WTG Configuration:	10 NTK 500/37H kW WTGs.
Years of Operation:	2 year (start up December, 1994).

Current Availability:	> 98.5% (Hours of Operation > 175,000).
Cumulative Production:	> 40,000 MWh.
Nordtank's responsibility:	supply and installation of WTGs. Five Year O&M, Service Contract
Remarks:	Extremely high energetic wind resource: mean wind speed > 10 m/s. During first two full years of operation: net capacity factor above 45%. During the winter months net capacity factor > 60%
Characteristics of the site optimization:	Nameplate Capacity 500 kW; Relatively small rotor, 37 meter; Relatively low tower, 33.8 m, resulting hub height 35 meter; Drive train has been reinforced due to extreme load spectrum Extra corrosion package due to coastal location.

c. Nordtank WTGs in extreme cold weather conditions.

More than 100 Nordtank wind turbines have been installed in locations with extreme cold weather conditions: locations where the wind turbines are consistently exposed to freezing conditions during the winter months and where the extreme low temperatures can go below -20 Degrees Celsius. The installation and operation of these wind turbine have given Nordtank the base for effectively optimizing its wind turbines for the extreme forces from the environment.

For our specific experience in the extreme cold weather conditions Nordtank would like to highlight its wind turbine installations in Finland, where the environmental conditions are getting very harsh: some wind turbines are even installed within the arctic circle where the extreme low temperature can go below -40 Degrees Celsius.

Various Individual Installations and Small Wind Farms in Finland:

Host Utility:	Various Finnish utilities
Current Owner:	Various, including: NAPS, Revonkatu 1, 86300 Oulainen, Finland tel. (358) 04501, fax. (358) 04505744
Name Plate Capacity:	5.5 MW.
WTG Configuration:	1 NTK 65 kW WTG; 5 NTK 150 kW WTG; 10 NTK 300/31 WTGs; 3 NTK 500/37 kW WTGs.
Year of Operation:	First WTG installed in 1991
Current Availability:	> 98% (Hours of Operation > 400,000).
Cumulative Production:	> 20,000 MWh.
Nordtank's responsibility:	Supply and Installation of WTGs
Characteristics of the site optimization:	Nameplate Capacity 500 kW; Relatively small rotor, 37 meter; Relatively low tower, 33.8 m, resulting hub height 35 meter; Cold Weather package that is including: 1. Special grades of steel for the structural components in the nacelles and the towers; 2. Heaters for the anemometer, wind vane, generator, gear reducer, slip rings and controller. The wind turbine controller has been specially outfitted for operations in cold weather conditions;

3. For some locations the cut-out wind speed has been customized for the site conditions:
 - To -20 Degrees Celsius (-4 Fahrenheit): 25 m/s.
 - From -20 to -30 Degrees Celsius (-22 Fahrenheit): 15 m/s.
 - Below -30 Degrees Celsius the turbines will not operate.

d. Nordtank WTGs in extreme hot weather conditions.

More than 200 Nordtank wind turbines have been installed in locations with extreme warm weather conditions: locations where the wind turbines are consistently exposed to mean temperatures above 25 Degrees Celsius and where the extreme high temperatures can exceed 40 Degrees Celsius. The installation and operation of these wind turbines have given Nordtank the base for effectively optimizing its wind turbines for the extreme forces from the environment. For our specific experience in the extreme hot weather conditions Nordtank would like to highlight the Planta Eolica Europea, a 6 MW wind power plant that has been installed in Tarifa – Spain, Europe’s most southern land tip, right at the street of Gribaltar. The environmental conditions at this site are pretty extreme:

- * The mean annual temperature is exceeding 20 degrees Celsius. During the summer months the mean temperature are exceeding 25 Degrees Celsius and during the days the wind turbines are consistently exposed to temperatures exceeding 35 Degrees Celsius
- * A mean annual wind speed in excess of 10 m/s

Planta Eolica Europea, Tarifa, Spain:

Host Utility:	Sevillane (Spanish Utility Company)
Current owner:	Planta Eolica Europea S.A Goya 85, E-28001 Madrid, Spain
Name Plate Capacity:	6 MW
WTG Configuration:	12 NTK 500/37H WTGs
Years of Operation:	One year, in operation since December 1995.
Current Availability:	> 98.5% (Hours of Operation > 125,000).
Cumulative Production:	> 20,000 MWh.
Nordtank's responsibility:	EPC contract, Five Year O&M, Service Contract
Characteristics of the site optimization:	Nameplate Capacity 500 kW; Relatively small rotor, 37 meter; Relatively low tower, 33.8 m, resulting hub height 35 meter; Drive Train has been reinforced; Hot Weather package that is including: • Extra attention to the cooling of the gear reducer and generator: gear oil cooler with extra capacity. • The wind turbine controller has been specially outfitted for operations in hot weather conditions; • Special types of lubrications.

V. CONCLUSIONS

The opening up of new and widely divergent markets is demanding an extremely flexible approach towards wind turbine construction. It is impossible to develop an all-round wind turbine, that will perform optimally in the wide range of project conditions: a single wind turbine design can not be outfitted perfectly for wind power plant installations ranging from Finland to Spain, from the New England region to windy mountain passes in Southern California.

Nordtank's flexible design concept ensures a well-balanced and optimal wind energy conversion solution for any given situation. The continuous development of Nordtank wind turbine technology and WTG components will further enhance the site optimization process in the future: In particular we expect to offer a wider range of rotor diameters, variable speed option and reinforced components for extreme site conditions.

NEW GUIDELINES FOR WIND TURBINE GEARBOXES

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Abstract

The American Gear Manufacturers Association in cooperation with the American Wind Energy Association will soon be publishing AGMA/ AWEA 921-A97 "Recommended Practices for Design and Specification of Gearboxes for Wind Turbine Generator Systems." Much has been learned about the unique operation and loading of gearboxes in wind turbine applications since the burgeoning of the modern wind turbine industry in the early 1980's. AGMA/AWEA 921-A97 documents this experience in a manner that provides valuable information to assist gear manufacturers and wind turbine designers, operators, and manufacturers in developing reliable wind turbine gearboxes. The document provides information on procurement specification development, wind turbine architecture, environmental considerations, and gearbox load determination, as well as the design, manufacturing, quality assurance, lubrication, operation and maintenance of wind turbine gearboxes. This paper presents the salient parts of the practices recommended in AGMA/AWEA 921-A97.

Introduction

In 1993 several manufacturers, researchers and consultants in wind energy felt the need for a document that could be used to develop more reliable wind turbine gearboxes. The American Wind Energy Association's (AWEA) Standards Coordinating Committee agreed to support the development of a gearbox standard for wind turbines under the AWEA Design Standards Committee. Representatives of this group approached the American Gear Manufacturers Association (AGMA) Technical Division with the idea of developing the standard jointly. After several joint planning meetings it was decided to develop a technical information sheet specific to the application.

Work began in July of 1993 and finished in October of 1996. The AGMA Technical Division Executive Committee approved it for publication in November of 1996, and AWEA Standards Coordinating Committee approval is currently pending. It is expected that AGMA/ AWEA 921-A97 "Recommended Practices for Design and Specification of Gearboxes for Wind Turbine Generator Systems" (1) will be available in August of 1997.

This Recommended Practice provides valuable information to assist gear manufacturers and wind turbine designers, operators, and manufacturers in developing reliable wind turbine gearboxes. It currently applies to wind turbines ranging from 40 and 750 kW.

Wind Turbine Application Complexity

Historically, gearbox problems have plagued the wind power industry since its major growth period in the 1980's. Many of these problems stemmed from a lack of understanding by both gearbox manufacturers and wind turbine manufacturers of the severity of the wind turbine operational environment. Off the shelf gearbox designs and normal load factor design approaches resulted in gearboxes that were inappropriate for the application.

The paucity of available loads data and limited experience with wind turbine gearboxes led to reliance on barely applicable "service factors". These are used by the gear industry as rules-of-thumb to typify the loading environment of known gearbox applications. This factor usually accounts for application specific experience that, in the case of wind turbine gearboxes, didn't exist. Unfortunately, this led to the use of inappropriate gearboxes, usually designed for other, less rigorous, applications.

A wind turbine gearbox is a speed increaser that increases the relatively slow speed of the rotor to the speed of the generator. The application is a demanding one that requires careful consideration of the load spectrum to ensure that the gearbox has adequate load capacity, and is within constraints on size and weight. Gearboxes must be designed to maximize efficiency while minimizing sound level. Because of the large number of wind turbines, and the limited accessibility for maintenance, reliability and maintainability are important considerations.

More recently, a better understanding of the unique load characteristics of wind turbines has enabled more reliable wind turbine gearboxes to be developed. This increased understanding stems from millions of hours of operation, failure analysis, open discussions between gear and turbine manufacturers, and an increased confidence in wind turbine load modelling and analysis.

Use of Document

The operation and loading of a wind turbine speed increaser are unlike most other gear applications. The intent of the AGMA/ AWEA 921 is to describe the areas wherein this difference manifests itself. Much of this is based on field experience. It is hoped that the document can be a tool whereby wind turbine manufacturers and gear designers can communicate and understand each others' needs in developing an appropriate gearbox for the application. Experience has shown that to be successful, the wind turbine designer should work with the gear designer to assure that gearbox loading is accurately defined for the wind turbine configuration being developed.

A specification for a wind turbine gearbox can be developed using Section 4 of AGMA/ AWEA 921 as a guide. Useful referenced documents and document definitions are listed in Sections 2 and 3, respectively.

The Annexes present informative discussion of various issues specific to wind turbine applications and gear design. All gear designers and manufacturers, even those familiar with the application, should read Annex A, wind turbine architecture, and Annex B, regarding the operating environment. Wind turbine manufacturers and operators should read Annex G on lubricant selection and maintenance, and Annex D on quality assurance. All parties should read about wind turbine loading in Annex C and recommended O&M practices described in Annex E. Finally, Annex F details the items to be included in the procurement specification.

Specification & Design Recommendations

This section is the meat of the document. It is a guideline for writing a procurement specification for wind turbine gearboxes. A thorough description of the application needs and requirements are

called for in a step by step manner. The wind turbine designer is encouraged to provide the gear designer with enough information to understand the application.

Minimum requirements for ratings, material specifications and manufacturing methods for gearbox components (such as gears, shafts, bearings, housing and the like) specific to wind turbine applications are included in this section. These minimum requirements are based on AGMA, ISO or ANSI standards or direct field experience. Also, certain gear elements, bearing configurations, seal types, and specific hardware are recommended for use (or not) based on operation and failure experience.

Gearbox components are discussed in depth, as are the manufacturing methods for gear elements. Explanation for the use of different gear elements and configurations are included for clarity. Specification of the lubricant system and detailing of all interfaces are also delineated.

Wind turbine architecture

It became apparent early in the development of the document that wind turbine engineers and gear designers were not speaking the same language. Many participants thought they knew the other's field enough to discuss the application in depth. This, however, was not the case. In light of this, it was decided to include a thorough description of the application and the impact on loading, structural integration and servicing of various configurations.

For this reason, Annex A describes the primary components that define the wind turbine configuration. Rotor orientation (horizontal or vertical axis), number of blades, control of rotor torque (blade pitching or stall control), and other items can have significant impact on the requirements of the gearbox. The committee felt it important to describe the configurational tradeoffs and impacts so that all parties understood the application.

For instance, modern horizontal axis wind turbines are moving toward a more integrated design. Instead of mounting a gearbox and generator on a bedplate with couplings and separate main bearings to support the blades, the structure is integrated to allow affixing the blades and rotor onto one end, the generator on another and then bolting it to the tower. Ancillary systems are mounted directly on the gearbox structure. This approach adds complexity to the gear housing design since it becomes a significant structural element transferring rotor forces and moments to the tower. For this reason AGMA/AWEA 921-A97 recommends a complete description of the wind turbine system configuration.

Environmental Considerations

The operational environment requires gearboxes that are resistant to temperature extremes, airborne contamination, and corrosion. AGMA/AWEA 921 recommends that a complete description of the anticipated physical environment should be communicated to candidate gear designers by wind turbine designers.

Wind Turbine Load Description

The wind turbine designer must determine the torque load spectrum for each condition that affects the gearbox using an acceptable method. However, determining the load spectrum is a difficult task due to a large amount of uncertainty associated with predicting operating and transient loads. In light of these difficulties, the document describes some useful approaches to assembling the loading description and provides references for further guidance (e.g., the IEC 1400 Wind Turbine Safety standard (2)).

Engineers and designers in the wind energy field have found through experience that the wind

turbine operational environment is unique. The following situations need to be tolerated:

- long periods of low speed operation during marginal winds;
- periods of small angular 'rocking' when the system is disabled but subject to winds nonetheless;
- temperature variations between sub freezing and desert environments; and
- rapid fluctuations in loads during normal operation.

The loads on a wind turbine are greatly affected by the system configuration and the control strategy. Two wind turbines with the same generator power rating may have extremely different gearbox torque load spectra. For this reason AGMA/ AWEA 921 describes the dominant configuration options and the impact of these options on gearbox design. Additionally, these descriptions help to familiarize gear designers with the components interfacing the gear system and their utility in the application.

Annex C was included to ensure that the loads are properly characterized to the extent required by the gear designer. A properly assembled load description includes a load spectrum and a description of significant transient events (e.g., application of a high speed shaft brake) and their expected frequency. Also, a description of the uncertainty involved in developing loads should be communicated to the gear designer.

Quality Assurance

Annex D of AGMA/ AWEA 921 provides a complete methodology for procuring gearboxes including:

- selecting gearbox manufacturers;
- auditing manufacturing and quality assurance; and
- acceptance testing of prototype and production gearboxes.

Operations and Maintenance

Annex E was included to provide guidance in developing start-up, maintenance and operating plans. This section is mostly experientially based recommendations from wind turbine operators. In addition, various considerations for safe and proper maintenance are provided to ensure that such items are included in the design process.

Procurement and Bid Documents

A complete roster of recommended documents required for a comprehensive procurement specifications are provided in Annex F in a checklist manner. A list of expected bid documents from candidate gear manufacturers is also provided.

Lubrication Selection and Monitoring

Proper selection and maintenance of a lubricant is essential to achieving maximum service life for wind turbine gearboxes. Annex G provides information on gear lubricant types, additive systems, and condition monitoring. In fact, we believe that this is the most thorough treatment of wind turbine gearbox lubrication and lubrication monitoring available in the industry.

Summary

Much has been learned about the unique operation and severe loading of wind turbine gearboxes since the early 1980's. New guidelines presented in AGMA/ AWEA 921-A97 incorporate this knowledge to help designers ensure reliable gearboxes for wind turbine service.

References

1. AGMA/ AWEA 921-A97 "*Recommended Practices for Design and Specification of Gearboxes for Wind Turbine Generator Systems*" AGMA, 1500 King St, Alexandria, VA 22314 USA, Tel (713) 684-0211
2. IEC 1400-1, "*Wind Turbine Generator Systems, Part 1: Safety Requirements*" IEC Central Office, 3 Rue de Varembe', Geneva, CH

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DIESEL PLANT RETROFITTING OPTIONS TO ENHANCE DECENTRALIZED ELECTRICITY SUPPLY IN INDONESIA

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Abstract

Over the last 20 years, the government of Indonesia has undertaken an extensive program to provide electricity to the population of that country. Electrification in rural areas has been partially achieved through the use of isolated diesel systems. About 20% of the country's generated electricity is produced by small, isolated diesel power plants employing over 1800 individual diesel units. Many factors associated with the use of diesel generators, from fuel cost and transportation to system maintenance expenses, have caused the Indonesian government and PLN to consider alternative methods for providing power to remote communities.

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Introduction

One of the most prevalent means of providing power to remote communities is the use of diesel generators. The appeal of this approach is the relatively low capital cost of the generating equipment. However, increasing problems associated with burning fossil fuels are motivating many institutions to consider alternative means of meeting growing demands for rural electricity. Such means include improving the efficiency of the diesel plants and adding renewable energy sources to the systems. Because the renewables (primarily wind and solar) fluctuate, combinations of renewables with diesel gensets are often considered to be the most practical solution. If renewables are not cost effective, other options for improving the efficiency of diesel plants may be considered.

Over the last 20 years, the government of Indonesia has undertaken an extensive program to provide electricity to the population of that country. Electrification in rural areas has been partially achieved through the use of isolated diesel systems. About 20% of the country's generated electricity is produced by small, isolated diesel power plants employing over 1800 individual diesel units. Many factors associated with the use of diesel generators, from fuel cost and transportation to system maintenance expenses, have caused the Indonesian government and PLN to consider alternative methods for providing power to remote communities.

In collaboration with PLN and Community Power Corporation (CPC), the National Renewable Energy Laboratory (NREL) has analyzed options for existing isolated diesel power systems. This study considered the use of different combinations of advanced diesel control, wind generators, photovoltaics, and batteries to reduce the consumption of diesel fuel and the overall cost of power generation. Analyses were conducted looking at typical diesel systems of many sizes and considered parametric analyses on system size, configuration, and renewable resource to allow general conclusions to be formed. The analysis also considered the potential of increasing the operation hours of some diesel plants.

In this report, five possible retrofit options are identified which can be used to reduce the use of diesel fuel. Each of these retrofit opportunities is described. Finally, several case studies are cited as examples of recommended designs. These case studies are based on analyses conducted as part of the NREL, CPC, and PLN study.

This report does not provide discussion on methods to reduce energy consumption or increase energy capture. An energy audit of a community should be conducted prior too, or as part of, any retrofitting plan to identify energy saving opportunities. In many cases, the load on a plant can be greatly reduced by incorporating energy savings measures like florescent lighting and power switches. One should also look for methods to productively use waste energy and manage non-critical loads so as to obtain peak output from the power system.

Advantages and Disadvantages of System Retrofits

There are a number of advantages for retrofitting diesel plants, in addition to the obvious reduction in fuel consumption. One can expect to reduce the number of operational hours on an existing diesel generator with well designed system retrofits. Because diesels are usually the piece of equipment with the highest maintenance cost and the maintenance costs are a direct function of operating hours, this will reduce the required maintenance expense of the system. There will also be a reduction in the pollution due to the reduction in use of the generators. If an advance system control is also installed, a reduction in the number of system operators can be achieved, even with an expansion of service. In addition, most system controllers also incorporate a measure of system performance monitoring and data collection that can be useful in long term system monitoring. The benefits of diesel retrofits are dependent on the system design and retrofit option chosen; these results will vary from system to system

There are a number of disadvantages to completing a retrofit on an existing diesel system. The primary disadvantage is the capital expense of the additional equipment; however in a well-designed system this is usually returned in a matter of years. The installation of new and additional equipment can cause technical difficulties due to the increased technical complexity of the system and the need to service and maintain multiple system technologies. There can be problems associated with the increased start/stop cycles experienced by the diesels with most high performance hybrid systems. Although the result of repeated start/stop cycling on diesel systems is documented (Bleijns et al. 1993), the decrease in diesel operation can greatly reduce the overall diesel maintenance.

Retrofit Options for Diesel Power Systems

Five different diesel system retrofit opportunities are described in this section. These five options are considered the most likely to have positive economic impact on the operation and maintenance expenses of the diesel system. As with any potential retrofit, the final retrofit option is highly dependent on the existing system architecture, generator sizes, and load profile for the community of interest. Depending on the system operational costs, it may be that no savings can be achieved through the retrofitting the diesel system. Any type or size of diesel system may be a candidate for retrofit, from the small, one diesel system providing power for only a few hours a day to large multi-diesel systems providing 24-hour utility grade power.

The five retrofit options to existing diesel systems are:

- Type A: Adjust the size of installed diesels or install an additional engine to provide diversity in unit capacity.
- Type B: Add automatic controls to existing diesel plant.
- Type C: Install batteries and a power converter to cover low load periods.
- Type D: Install wind turbine generators and/or PV array to reduce diesel generation.
- Type E: Installation of an advanced renewable/battery/diesel hybrid power system.

Type A: Adjust diesel size or install an additional diesel engine

One of the ways of reducing the costs of operating an existing diesel plant is to insure that the generators are properly sized to the community load. Appropriate sizing of generators is important in systems of all sizes, from small, single generator systems to large multi-generator power plants. Typically the diesel engines in a remote power station are sized to adequately cover the yearly peak load and are thus oversized for normal day to day operations. Depending on the size of any existing generators and the community's load

profile, the replacement of, or even the installation of a new, smaller diesel unit may result in a very quick return on investments. This is described graphically in Figure 1, where the fuel curves for two representative diesels are shown. A village with a maximum yearly load of 300 kW may have a 330-kW diesel installed to meet this load. The average daily load is only about 100 kW, so installing a smaller generator to cover the standard load could save about 15

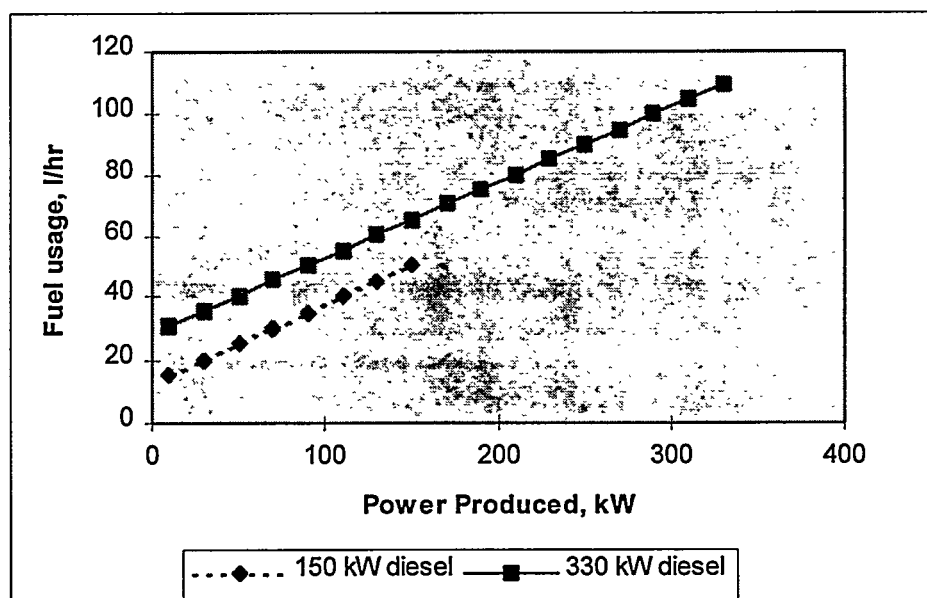


FIGURE 1. COMPARISON OF DIESEL SIZES TO MEET A SPECIFIED LOAD.

liters of fuel for each hour of operation. The larger diesel would then be used during times of high load or as a backup when the first diesel is undergoing maintenance.

Type B: Add automatic controls to an existing diesel plant

Larger diesel plants often contain multiple diesel engines of various sizes. In these systems, it is more likely that the diesels will be the appropriate size; however, the diesels operating at any given point may not be the most efficient combination to cover that load. In these systems, controls can be placed on the diesel generators to enable automated dispatch and more efficient operation. Each genset is provided with controls for auto starting, synchronization, and load matching while a master control is used to coordinate diesel dispatching and load sharing. Automated systems have the additional advantage of detailed operational data collection and monitoring. Fuel savings depend on the current system design and dispatch strategy, but tend to be cost effective in larger systems where the current dispatch strategy is either inefficient or labor intensive. The use of advanced controls may add a level of technical sophistication that will only be appropriate in larger communities.

Type C: Install batteries and a power converter to cover low load periods

This approach is applicable in a single-diesel system if the community has periods of the day with very light loading compared to the peak load. In these cases, the existing diesel is generally oversized for the low load period, thus it operates with poor efficiency. A retrofit battery bank and power converter, where stored energy from the battery is used to power the converter and cover the load, allows the generator to be turned off during periods of light loading. The batteries are then recharged when the generator is operating at higher efficiency. This approach may also be used to expand the hours of service of a particular plant without greatly increasing the system operation costs. In multiple-diesel systems, the addition of batteries can preclude the need to start an additional generator that must run at low loading to cover fluctuations in power over the rating of the primary generator. In either case, the generator recharges the batteries during other periods of the day. The decision of whether to install a converter/battery bank or a smaller diesel to cover these low load periods is dependent on the ratio of low load to diesel size and should be considered carefully. The potential cost savings depend on the load profile and the sizes of the diesel generators. The size of the battery bank depends on the energy requirements of the low load period. The size of the inverter depends on the magnitude of the load during the low load period. Both the initial cost and the periodic replacement cost of the batteries must be weighed against the reduction in operation and maintenance expenses. This concept is shown graphically in Figure 2. In this system the batteries cover the load in the early morning and then are recharged by the diesel later. 27 liters of fuel is saved each day versus the original all-diesel system.

Type D: Install wind turbine generators and/or PV array to reduce diesel operation

Wind retrofits to diesel power plants are primarily useful in large systems with good wind potential and high fuel costs. In plants with many large diesels, where there is always a demand for power, the wind power is used to

offset power production by the generators. The addition of the wind power may also reduce the number of generators operating at any given time, thus reducing the diesel maintenance requirements.

Because system dynamics and power stability are of primary concern, at least one diesel generator is operated continuously and the wind penetration is

usually only a fraction, from 20% to 50%, of the average load. Advanced controls are usually included with these systems to allow for the shutdown of individual wind turbines and/or diesels depending on the resource, load, and system control requirements. This approach can be very cost effective but is capital intensive due to the cost of the wind turbines and controls. The potential cost savings depend on the wind resource, diesel maintenance costs, and the fuel price. Based on current prices, PV is usually not cost effective in large systems when compared strictly to the marginal cost of diesel fuel. Figure 3 shows the

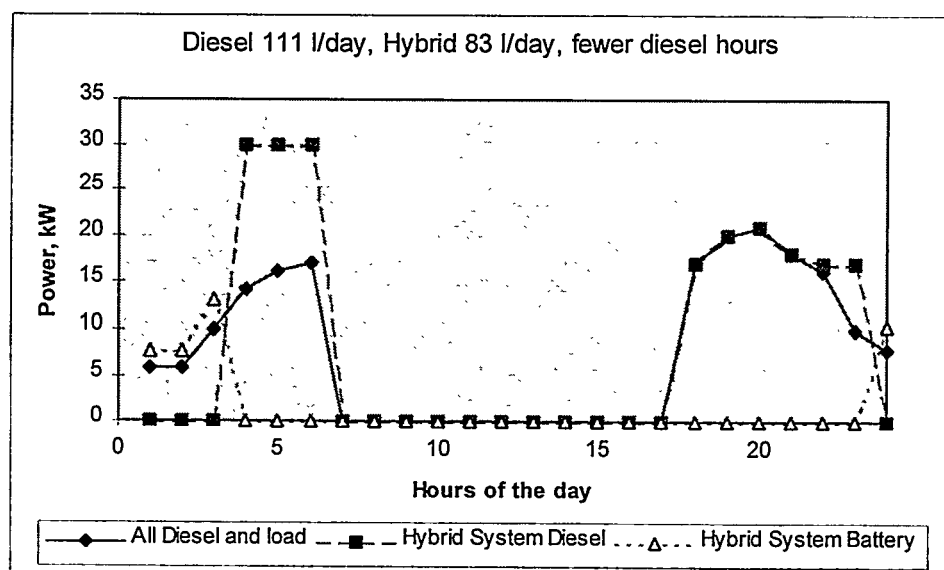


FIGURE 2. DIFFERENT MODES OF OPERATION FOR A BATTERY/DIESEL ONLY POWER SYSTEM.

hypothetical results of installing wind turbines and controls onto a diesel system. The wind power is used to directly reduce the load on the diesel engines. With the use of wind power, a smaller diesel may also be used to cover the remaining load, which will also result in larger operation and maintenance savings.

Type E: Installation of an advanced renewable/battery/diesel hybrid power system

In this case, a diesel system is retrofitted with both renewables and a battery bank. During times of high renewable production, wind and/or solar power is used to meet the community load and to charge the battery bank. When the renewable power is less than the load, either the batteries or the generator cover the shortfall. If the

batteries become depleted, the generator(s) are started to cover the load and perhaps charge the batteries. The combination of renewables and batteries has the potential of reducing the diesel fuel usage to a very small portion of the amount required in a diesel-only system.

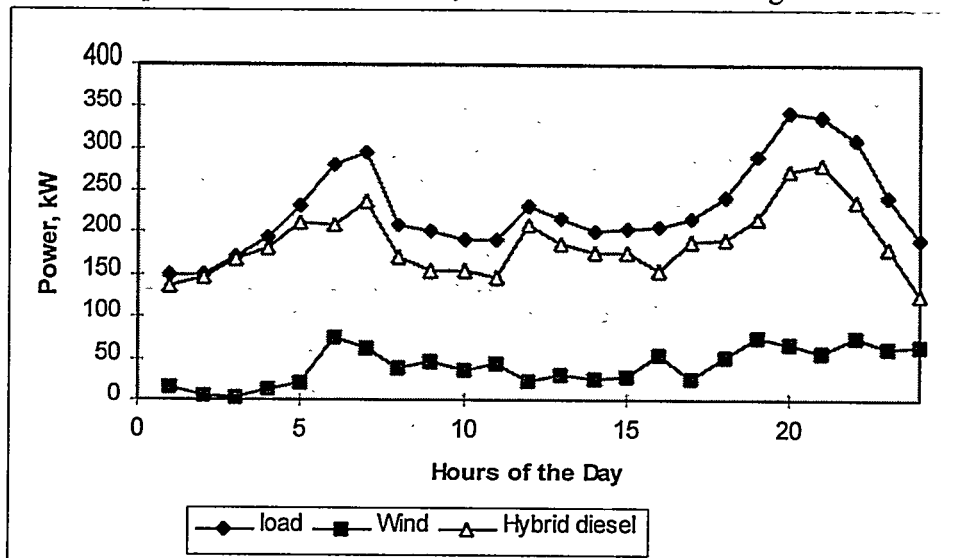


FIGURE 3. DIESEL POWER REDUCED BY THE INCLUSION OF RENEWABLES.

The fuel savings, along with savings in diesel maintenance

costs, must be weighed against the high system capital cost and the periodic replacement of the batteries. Diesel systems of any size can be retrofitted with renewables and batteries, although the system design and control will likely change dramatically. The size and purpose of the battery bank will also vary greatly depending on the available resources and system costs. A

general size description for batteries is given in the following section. Hybrid system cost-effectiveness is highly sensitive to the abundance of the renewable resource, diesel maintenance costs, and the diesel fuel price. A 24-hour graphical description of system operation is shown in Figure 4. This system shows the

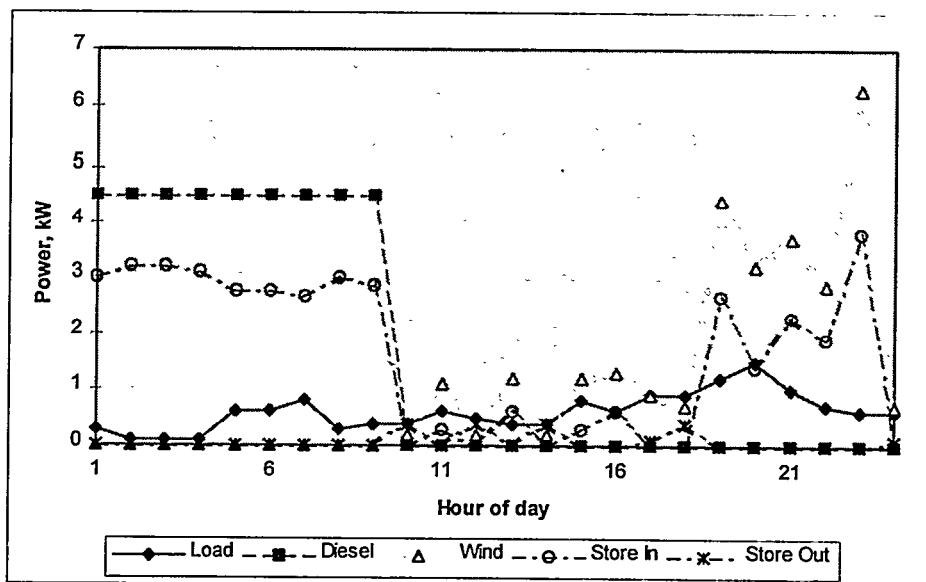


FIGURE 4. OPERATION OF ADVANCED HYBRID SYSTEM

diesel operating in the morning to cover the load and charge the batteries. After this the batteries and renewables cover the load until evening when the batteries are again charged, but this time by the wind.

Storage Requirements for Hybrid Power Systems

The amount of storage capacity, based on the approximate time of load-coverage capacity, may fall into one of the following categories. The appropriate level of storage depends on the cost trade-off involved at each stage in this progression and the general size of the power system.

1 to 7 minutes: Used to cover short turbulent peaks in the wind and to start generators, if required.

Batteries are designed for high rates of discharge over short time periods to maintain grid stability.

7 to 30 minutes: Meet fluctuations in the net load (load minus renewables), thus allowing any diesels to remain off until it is clear that the lull in the winds is not a short-term fluctuation.

Hours: Allow diesels to run at rated capacity, rather than at part load, to maximize diesel fuel efficiency, storing the excess in the batteries to be used when beneficial for the system.

Hours to days: Time-shift an abundance of wind or solar energy to match the load. This is mainly applicable in places with small loads or where the operation and maintenance costs of a generator are larger than the cost of storing renewable power in the batteries.

Assessment Procedure

The process of retrofitting diesel systems is rather complex and requires the collection of resource and existing performance data to evaluate the available retrofitting options. A performance and economic analysis should then be completed to determine the economic benefit of the different options. Before this task is undertaken, it is necessary to determine if a particular system should even be considered for system retrofit. The following are some general indications that a diesel power plant would be a good candidate for retrofitting.

1. A large difference between diesel system-rated power and the average load for the community being served.
2. Large variations in the community load from the minimum to peak load.
3. If the plant diesels are spending long periods running at low power levels or at idle.
4. There are many system faults due to operator or systems errors.
5. High fuel costs including both purchase and transportation charges.
6. A local source of renewable energy such as sun, wind, or hydro.
7. High system costs due to maintenance or other problems.

Case Studies: Small and Large Systems in Indonesia

Indonesia, the fourth most populous country in the world, consists of 13,667 islands, of which at least 3,000 are inhabited. PLN operates in excess of 1,800 diesel power plants, which produce about 20% of the country's generated electricity. Of these diesel plants, 1,100 are below one MWe in total nameplate capacity and are widely distributed geographically, making fuel delivery, reliable operation, and maintenance expensive, time consuming, and difficult. Regulated tariffs on the generated electricity are causing PLN to lose money on the diesel plants, even with the price of diesel fuel fixed at \$.17/liter. To limit costs, electrical service is limited to a few hours per day in some areas. In response to this need, the Indonesian government and PLN are considering alternative methods for providing power to remote communities. Three case studies that were part of the original study conducted by CPC, PLN, and NREL are described below. These case studies provide examples for some of the retrofitting options discussed above.

Case 1: Small system with good wind and solar resources

The diesel plant at Pariti is typical of many in Indonesia in that electrical service is provided only 12 hours per day, with the load profile shown in Figure 5 (solid curve). In this analysis, we

consider the addition of a small daytime load shown with a dashed line and various retrofit options. Providing 24-hour power opens the door to the development of productive uses of electricity, such as micro-enterprises or small industry. The existing power system at Pariti consists of two 20-kW diesel gensets. Because the wind resource at this site is unknown, a scenario typical of many locations throughout Indonesia, wind speed data set from the nearby site of Sakteo, averaging 5.56 m/s at 30 m, was used in the analysis.

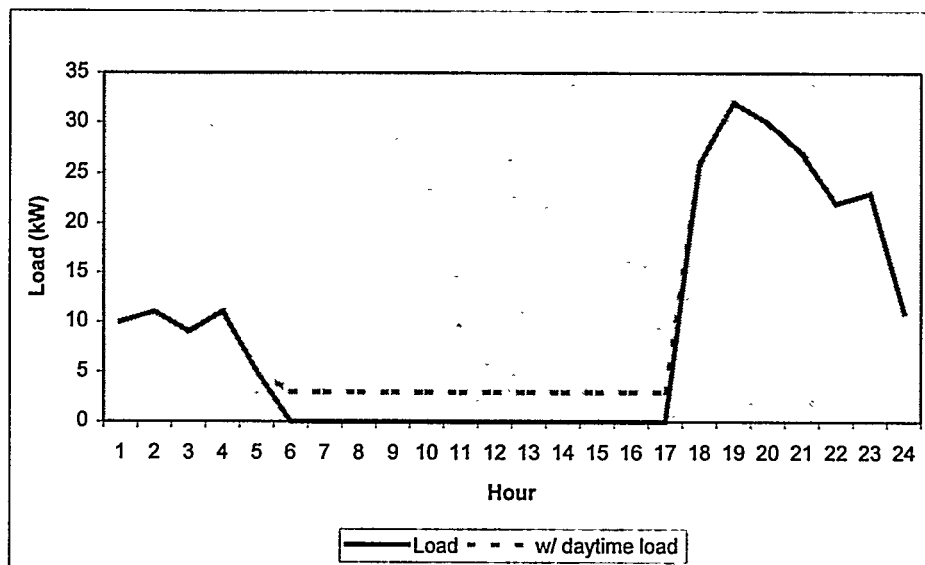


FIGURE 5. LOAD PROFILE AT PARITI WITH A 3-KW DAYTIME LOAD ADDED.

Similarly, the annual average solar radiation, based on data from the nearby Kupang airport, is 4.4 sun-hours/day (kWh/m² day). These analysis were conducted using the Hybrid2 software (Baring-Gould et al. 1996).

Retrofitting the existing diesel plant with renewables and batteries to form an advanced hybrid system while providing 24-hour operation will result in only a minor increase in cost over the existing all-diesel system that provides power for only 12 hours a day. The results of the different options are given below.

TABLE 1. A COMPARISON OF VARIOUS RETROFIT OPTIONS

System Type	Service Period	New Equip. Cost, \$	Fuel Use, l/y	Life-Cycle Cost \$ (fuel @ \$.17/l)	Cost, \$/kWh (\$.17/l) (\$.34/l)	
Existing	12-hour	0	30,397	430,144	0.28	0.35
Existing	24-hour	0	46,383	697,377	0.38	0.48
Type B	24-hour	10,000	46,383	551,037	0.30	0.40
Type C (w/ controls)	24-hour	27,240	34,093	501,581	0.28	0.35
Type E (Wind)	24-hour	60,440	26,979	482,718	0.27	0.32
Type E (PV)	24-hour	55,240	31,850	507,192	0.28	0.35

Some of the recommendations resulting from the analysis are as follows;

1. For 24-hour service, controls and batteries are cost effective.
2. Measured wind and solar resources are needed for candidate sites. Wind turbines are cost effective at Pariti for this load scenario and a fuel price of \$.17/liter, at wind speeds of about 5.6 m/s or greater. Photovoltaics are cost effective at a fuel price of about \$.34/liter or greater.

3. Pilot projects for small diesel grid systems are recommended to demonstrate the feasibility of the approach.

Case 2: Large system with good wind resource

The analysis conducted looks at the potential inclusion of wind power into the large diesel plant in So'e, Indonesia. The inclusion of the advanced system controls and wind power could significantly reduce the consumption of diesel fuel and reduce the total number of diesel run hours. The analysis was expanded using parametric analysis to consider systems of similar size, where the fuel and wind potential may be different. The analysis considered various average wind speeds, wind penetrations, diesel fuel price, and different financing mechanisms. The retrofit systems considered did not include solar power due to the system size and available solar resource. The average load for the site was 505 kW and was supported by four large diesel gensets. The power plant provided power 24 hours a day and was controlled manually.

The basic result from the analysis is that given a delivered fuel cost of \$0.17/l and an average annual wind speed of 5.56 m/s, the system is marginally feasible from a financial viewpoint. Similar systems in areas with higher fuel prices or wind speed should show dramatic economic viability, saving anywhere between \$0.10 to \$0.50

/kWh produced, as shown in Figure 6. In this type of system the potential for fuel savings increases as the installed capacity of the wind turbines is increased. This is shown in Figure 7, where the number of 50-kW wind turbines was increased from zero to 10 using a wind speed with an annual average of 5.56 m/s. Above about 300 kW of installed capacity, there is a diminishing return on the installation of additional turbines because, during high wind

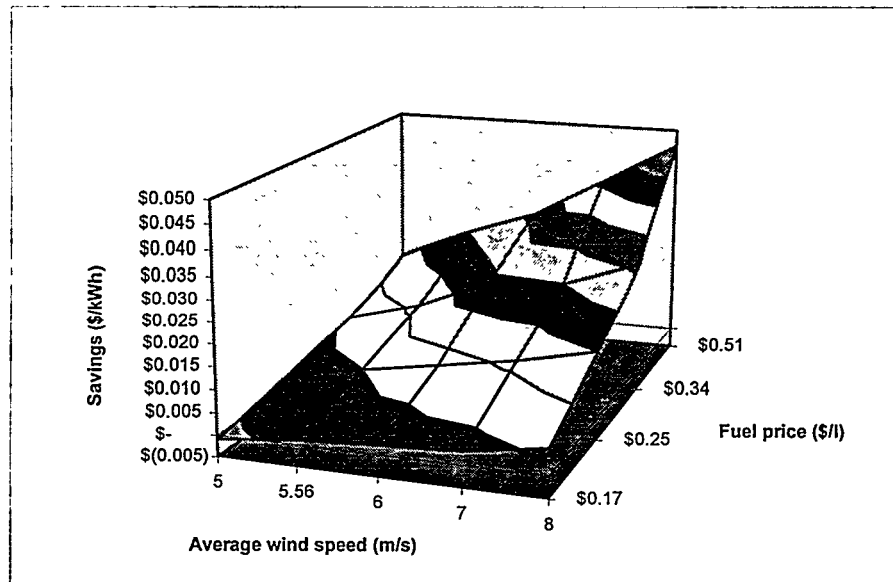


FIGURE 6. PARAMETRIC SAVINGS FOR WIND INSTALLATION

periods, more power is being generated than can be used. It should be again noted that above about 20% penetration of wind power, serious consideration must be given to power system dynamics to insure high quality, consistent power.

In addition to the analysis of using wind power to augment the diesel production for the So'e power plant, a simple control retrofit was also studied. In this analysis, the operational characteristics of the present diesel plant were compared to a version of that plant operated by an advanced control system. In addition, an analysis was conducted in which one of the larger diesels was replaced with a smaller one that could more efficiently provide power for periods of low load. The analysis showed that the cost of implementing the controls could be paid back in as little as 2 years. It was also found that the number of diesel starts was increased using advanced control, but that the total diesel run time could be reduced by almost half. This results in a large decrease in diesel O&M and overhaul costs. System savings of between \$0.03 and \$0.05 /kWh were produced with a very small outlay of approximately \$50,000.00 for

system and individual diesel controllers. Installing a smaller diesel to provide a better diversity in unit capacity was also shown to be cost effective.

Case 3: Moderately-sized diesel system without available renewable resources

The town of Lonthoir, Indonesia, is a large community that is provided power using two diesel engines. The town has power for 13 hours a day, from 5 p.m. to 6 a.m., and a base load of approximately 60 kW for services like street lighting and refrigeration. The load increases during the morning and evening up to about 135 kW. Because power is not available during the day, mainly due to the current tariff structure, no business or other productive uses of power are being realized.

A power system was designed incorporating a battery storage bank and converter to allow the generators to cover the average load while using the battery bank to cover any fluctuations above the rated level of that generator. Due to the lack of data demonstrating a wind or solar resource, renewables were not considered. An analysis considering two fuel costs and converter/battery sizes was also completed. Incorporation of a small daytime load and upgrading the system to provide 24-hour power was also considered. These analysis were conducted using the Hybrid2 software.

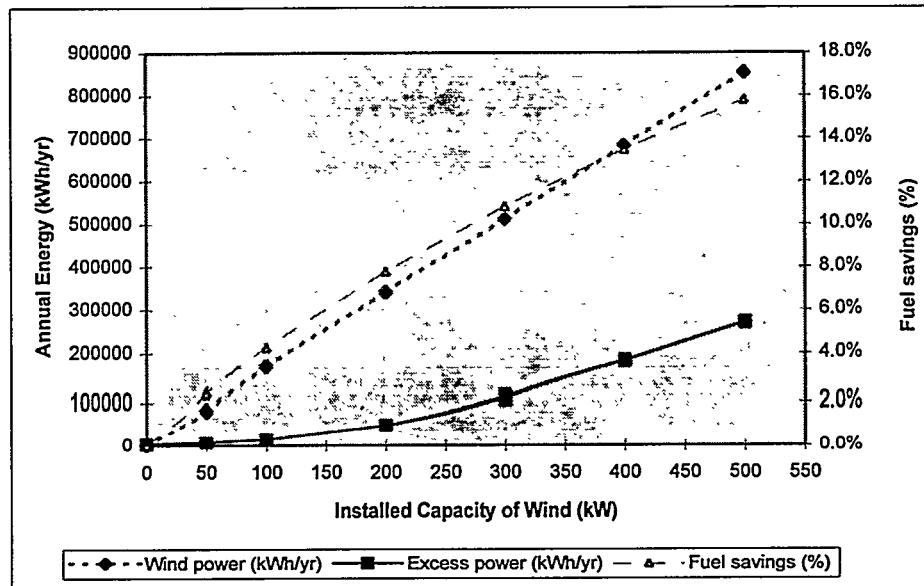


FIGURE 7. PERFORMANCE VARIATION WITH INSTALLED WIND CAPACITY

Using a battery and converter saves money for either 13-hour or 24-hour power systems. The projected savings ranged from 1 to 5 cents for each kilowatt-hour produced. During the evening, the average load never goes above the rating of the 140-kW diesel, but fluctuations in the load do. A 20-kW converter and battery bank combination covers these fluctuations and makes the second 100 kW diesel unnecessary, (Figure 8, next page). In a 24-hour system, the battery bank is used during the daytime. This allows both of the diesels to be shut off when the load is low. The battery bank is then recharged during the evening and early morning when a diesel is forced to operate.

Conclusions

In any existing diesel power plant, it is quite likely that some improvement in economy of operation can be achieved through one of the approaches discussed in this paper. In many systems the diesels are oversized and significant improvements are possible merely through improved genset sizing. When even properly sized diesels operate at low loading much of the time, the addition of batteries is likely to be cost effective. The cost-effectiveness of adding wind and/or solar generators to the system depends primarily on the abundance of the renewable resource and on the fuel price. Of all the retrofit options, the greatest diesel fuel savings may be obtained by combining renewables with batteries. A time-series model, such as Hybrid2, is needed to properly analyze and compare the design options. Often, the most

challenging aspect of the assessment of diesel retrofit opportunities is obtaining accurate resource data.

This analysis demonstrates two main points. Initially there are many options that governments, utilities and local groups can use to improve the

operation of existing diesel power systems. Using the techniques discussed in this

paper enables these organizations to free up funds now being spent on simple operation and maintenance. This capital can then be used to expand service to other rural areas. The second point that this paper makes clear is that there is a great deal of opportunity for the use of renewables and diesels, not only in new systems but in many older power systems worldwide. It should however be noted that this is a paper study and that systems implemented using these retrofitting options may result in different savings than are expressed. In addition, rural areas usually provide very different engineering experiences than urban centers and technology that has been proven in the latter may not provide the same performance in the former. However, with the expansion of power needs worldwide, the emphasis now being placed on environmentally friendly energy systems and the reluctance of many governments to be tied to volatile fuel prices, the potential for effective diesel retrofitting and the installation of new hybrid power systems has never looked better.

Acknowledgments

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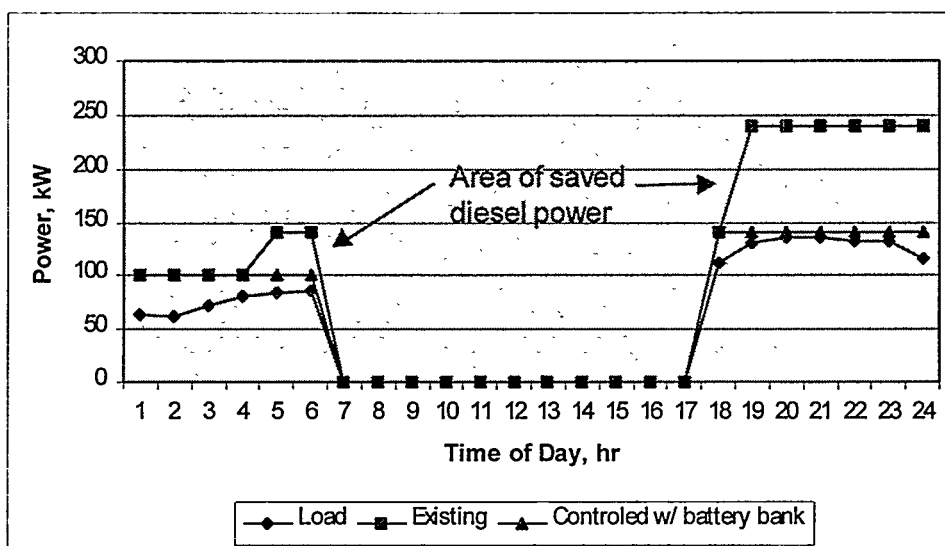


FIGURE 8. RUNNING DIESEL CAPACITY FOR ORIGINAL AND RETROFIT SYSTEMS

COSTA DE COCOS 11-kW WIND-DIESEL HYBRID SYSTEM

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ABSTRACT

Costa de Cocos is a small resort located in the state of Quintana Roo, Mexico. Using the existing diesel generator, the resort's power system was retrofitted to a wind-hybrid diesel system. The reason for this retrofit was to supply 24-hour power, to reduce diesel fuel by using wind energy, and to reduce diesel air and noise emissions in order to promote ecotourism. The wind system was installed in October 1996 with cost-shared funding from the U.S. Department of Energy/U.S. Agency for International Development renewable energy program in Mexico. The National Renewable Energy Laboratory (NREL) supplied technical assistance to the project. Discussed in this paper are the system design, installation, and initial performance.

BACKGROUND OF COSTA DE COCOS RESORT PROJECT

Costa de Cocos is a small scuba diving and fishing resort located in southern Mexico in the state of Quintana Roo, about three kilometers from the isolated town of Xcalak. Prior to the installation of the wind system, the owner used a diesel generator for part-time power. The owner would charge batteries with the diesel during the day and use the batteries to power small loads in the cabanas and restaurant during the evening. This had the benefit of not having to run the diesel all night long. However, the owner found that this system did not supply enough power to meet the evening loads. In addition, the owner was interested in installing a reverse osmosis machine to desalinate seawater for use by the resort. This was significant because desalination requires high energy input.

A major reason for installing the wind system was to save diesel fuel and reduce maintenance costs. Fuel costs about \$0.50 per liter (including fuel transport costs) and the fuel savings over the life of the project are substantial. In addition, maintenance of the diesel is a continuous burden for the owner and reducing diesel run-time would result in less maintenance and less overall reliance on the diesel. The displacement of diesel emissions and diesel noise is appealing and especially attractive to customers who identify with "green" low-impact tourism. The surrounding area is full of natural ecological attractions and the owner anticipates that business will improve by making the facility more environmentally friendly.

Cost-shared funding for the project was available through a program sponsored jointly by the U.S. Agency for International Development (AID) and the U.S. Department of Energy (DOE), which is promoting the use of renewable energy in Mexico. This program is especially interested in renewable energy projects that promote "productive uses" of renewables, i.e., uses of energy that bring income to the end-user.

WHY ECOTOURISM HOTELS FOR WIND-HYBRIDS?

There are a number of reasons why ecotourism hotels are a good place to install wind-diesel hybrid systems: the owner has an ability to pay for the system with cash flow from the business; financing is often available because the owner has equity; there are usually good technical skills available at the site from previous experience with the existing diesel system that are important for operation and maintenance (O&M) of the hybrid system; there are good winds at coastal ecotourism sites because of trade winds and coastal sea-breeze effects; energy conservation and load management are easier to implement than with a larger village system; and the idea of "green marketing" appeals to many small resort owners and their customers. With larger mini-grid renewable systems for villages, such as the nearby Xcalak wind-PV hybrid system, the institutional arrangements of running a small utility service, including metering energy use and billing customers, can be challenging. This is not the case with a small wind-hybrid system for a private resort. If done correctly village mini-grids are sustainable, but they are a different market and can be harder to implement than small ecotourism resorts, hence it makes sense to commercialize systems in less difficult applications so that a good track record is achieved early on.

TECHNICAL DESIGN OVERVIEW OF THE COSTA DE COCOS SYSTEM

The following steps were taken in the implementation of the system.

- 1) Estimate existing and future loads and analyze types of loads.
- 2) Estimate wind resource and existing diesel fuel consumption.
- 3) Preliminary sizing of generation system based on available commercial equipment and budget.
- 4) Computer modeling of the system, including sensitivity analysis of battery storage, loads, diesel run time and dispatch, load management, and estimate diesel fuel savings.
- 5) Develop bid specifications.
- 6) Install system (October 1996).

Several different load scenarios were developed, based on seasonal variations and inclusion of a reverse osmosis (RO) machine (it was unclear whether the owner would buy the RO machine until the end of the project design phase). Besides the RO load, other major loads were the clothes washer and dryer, lighting, refrigeration and two freezers, kitchen appliances, an icemaker, and miscellaneous workshop tools. Figure 1 shows a peak season load profile with and without the RO system; note the large energy requirement of the RO system.

As can be seen from the load profiles, the peak energy use is in the middle of the day. This was defined by the owner because some of the loads could be turned on at any time in the day (i.e., deferrable loads). If the diesel is needed to meet the load, it will usually be during this peak load time. Having the peak load in the day allows for the diesel to be run when the noise will be less bothersome. In reality, the owner could manage the deferrable loads from the morning through the night so as to have the peak load coincide with the highest daily wind speeds, should the wind speed vary during the day. During peak seasonal load the diesel would meet the RO load during the midday peak because there would not be enough wind energy available. All the loads in the resort are single phase, requiring a single phase distribution system. All loads are 120 volts except the RO load, which is 240 volts.

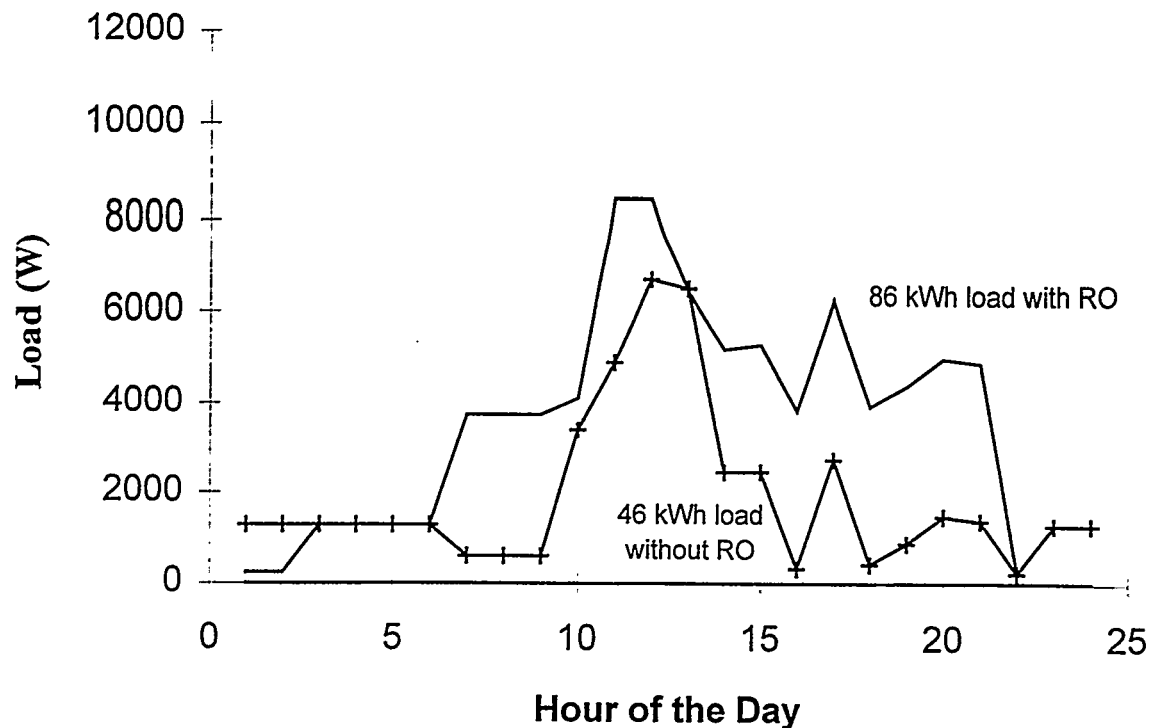


FIGURE 1. DAILY LOAD PROFILE - 46 KWH/DAY NO REVERSE OSMOSIS AND 86 KWH/DAY WITH REVERSE OSMOSIS AT PEAK SEASON

After estimating the load, the next task was to estimate the wind resource. Available wind speed data from the Xcalak anemometer indicated an annual average wind speed of 6.1 m/s at a 30 meter anemometer height. Low wind season is usually during October and November (average monthly wind speed about 4.9 m/s), which coincides nicely with the load demand because low tourist season for the resort is September thru November.

SYSTEM ANALYSIS

The NREL Hybrid2 simulation code (Baring-Gould et al., 1993) was used to model the system and calculate appropriate turbine and battery sizes. Hybrid2 is a time-series/probabilistic model that uses time-series resource and load information, along with manufacturer's data for hybrid system equipment, to predict the performance and cost of hybrid power systems. The basic system architecture modeled was an AC permanent magnet alternator turbine connected to a 48-volt DC bus via a wind turbine charge controller/rectifier for charging flooded lead acid batteries. The DC bus, consisting primarily of lead-acid batteries, is then connected to an inverter system to power the AC loads. The load profiles shown in Figure 1, adjusted for seasonal variations, were used as inputs along with hourly average wind speed data for Xcalak.

The largest recurring cost in a wind-hybrid system with energy storage is battery replacement. Different types of batteries were analyzed and lifetime for the batteries was calculated for a given battery bank capacity. For example, a battery bank comprising 350 amp-hour lead acid batteries (6 volt cells) was

compared with the same capacity battery bank comprising tubular 500 amp-hour batteries (2 volt cells). Lifetime estimates were developed for the batteries by dividing the manufacturer's data on energy throughput by the annual energy cycled through the batteries as estimated by Hybrid2 (the load scenarios were the same for each battery type) to calculate battery lifetime in years. This lifetime was then reduced by 25% to account for accelerated lifetime degradation because of higher temperature. (Manufacturers' data for battery life is for 25 degrees C and the average annual temperature at the site is about 10 degrees C higher; a rule of thumb is that battery life can degrade from 25%-50% for every 10 degrees C above 25 degrees C, with calcium lead-acid batteries being affected more by this phenomena than antimony lead-acid batteries as used here). Based on the Hybrid2 modeling, the costs for the less expensive, lower amp-hour capacity batteries (i.e., 350 amp-hour) were found to have a lower life cycle cost even though they had to be replaced more often.

Modeling results indicated higher fuel savings with 20 kW of wind power; however, project funding was only available for a maximum of 10 kW of wind power. Base case modeling consisted of a diesel-only system, with inputs for diesel O&M and overhauls estimated based on current experience and costs. Fuel costs were estimated at \$0.50/liter including transport.

Based on the computer modeling and the preliminary system design, bid specifications were developed for the system and included in a competitive request for proposal (RFP). The bid was awarded to Bergey Windpower Company of Norman, Oklahoma. Costs for the equipment are listed below. A simplified system schematic is shown in Figure 2.

TABLE 1. CAPITAL COSTS FOR EQUIPMENT AND INSTALLATION

7 kW Wind Turbine	\$12750
Tower	\$7626
Charge Controller	\$1700
2 -5.5 kW Inverters	\$6800
Battery System	\$4992
Misc. Hardware	\$450
AC Load Center	\$714
System Wiring	\$1370
DC Source Center	\$1200
Installation and System Testing	\$6600
System Documentation	\$300
Shipping and Insurance	\$3750
Travel Expense	\$1953
Warranty	\$1250
Battery/Inverter Structure	\$950
Customs	\$4224
<u>TOTAL</u>	\$58,315

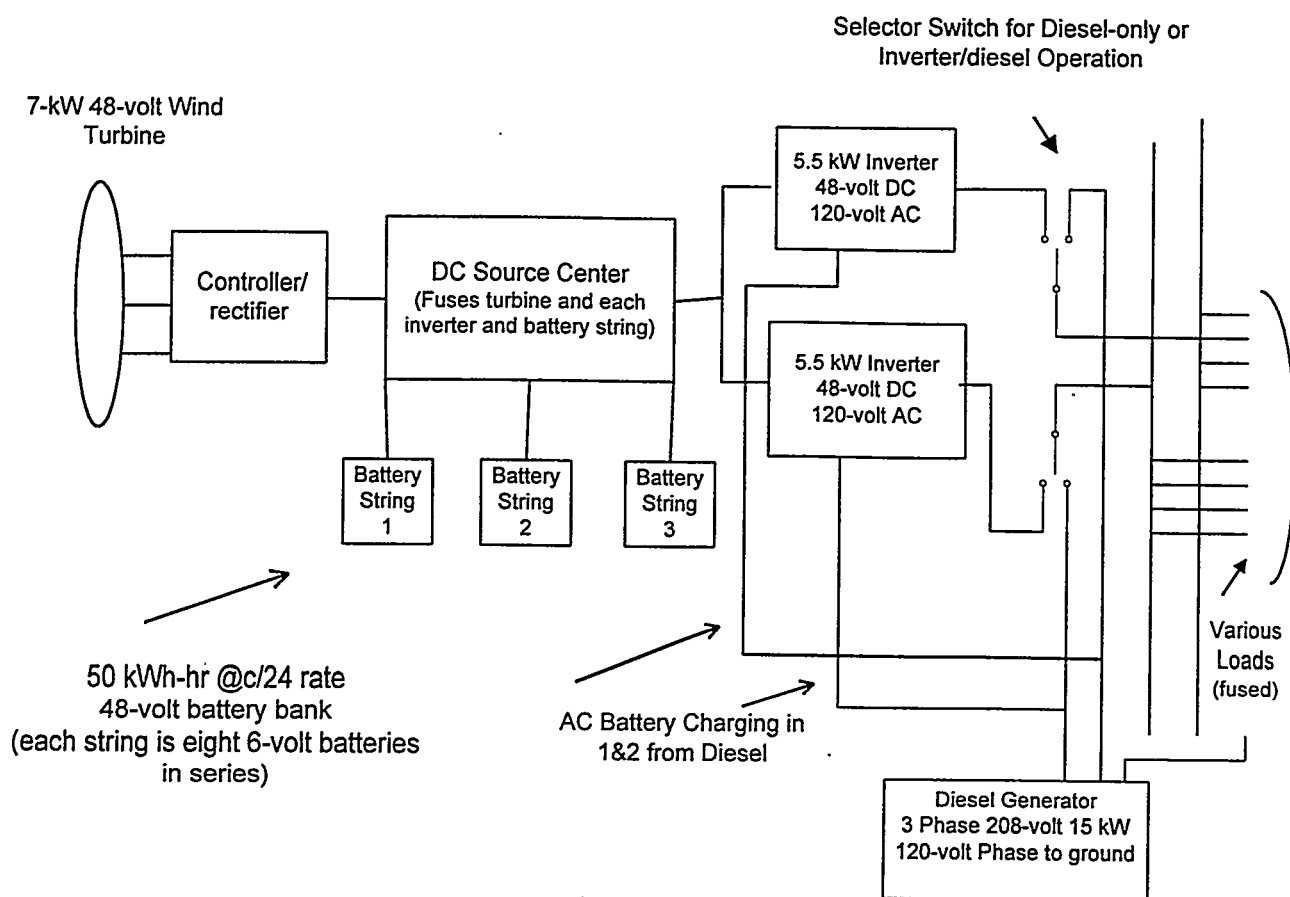


FIGURE 2. GENERAL HYBRID SYSTEM SCHEMATIC

EQUIPMENT DESCRIPTION

A Bergey EXCEL wind turbine was selected for the project. A unique feature of this turbine, which is different from previous EXCEL turbines, is that it has a 48-volt winding, so there is no need for a step-down transformer that is required for the more common 240-volt winding when the turbine is connected to a 48-volt DC bus. The 48-volt winding can be used in this application because the wire run from the turbine to the DC source center is short and thus resistive wire losses are within acceptable limits; usually wire runs are longer and a higher voltage winding is needed to prevent excessive wire losses. In this case not having a step-down transformer saved about \$1000. However, the main reason for going to the 48-volt winding was to provide a better match between rotor output power and generator impedance for the given wind regime, thereby increasing the power output. (The Bergey EXCEL turbine produces about 10 kW when connected to a utility grid but only about 6.5 kW when connected to a fixed voltage load such as a battery bank. The stator winding can be changed to provide for better maximum power in high wind speeds, but this results in the turbine cutting in at a higher wind speed and hence energy is lost at low wind speeds. As will be discussed in a subsequent section, the maximum turbine output appears to be about 7 kW, although more information still needs to be collected.)

A problem with the Bergey EXCEL turbines at the nearby hybrid power system in Xcalak was their vulnerability to the high salt spray environment. Substantial improvements were made to the Costa de

Cocos turbine to prevent saltwater corrosion. These improvements included stainless steel fasteners and pitch weights; special inorganic zinc coatings to the blade bolts (i.e., mounting studs); epoxy encapsulated stator winding; hot dipped galvanized tower bolts; and a petroleum-based corrosion inhibitor for the guy wires. These important improvements are expected to mitigate the adverse effects that corrosion had on the Bergey turbines in Xcalak resulting in lower O&M costs for this system.

The wind turbine tower is a lattice, tilt-up tower. This tower is easier to install than a non-tilt-up tower that is erected using a gin pole because all the installation work is done on the ground, including both tower construction and attaching the turbine to the tower. Compared to a tubular tilt-up tower, the lattice tower is easy to climb for inspection and most O&M tasks can be performed without lowering it to the ground, making it easier to do maintenance than with a tubular tilt-up tower. It is estimated that using a tilt-up tower saved two days of installation time compared to using a non-tilt-up tower. Also, the Xcalak region is prone to hurricanes and a tilt-up tower can be lowered in about a half hour should the site be at risk for a direct hit from a hurricane. A tilt-up tower does take more space than a non-tilt tower because the guy wires have to be raised from an angle during the tilt-up.

As can be seen from the system schematic in Figure 2, the variable voltage AC power from the wind turbine is rectified by the controller. The controller also regulates the current above a high voltage regulation limit of about 56 volts using SCR (silicone controlled rectifier) switching. As a result of the current regulation, the turbine becomes unloaded in proportion to the amount of current being regulated, and turbine RPM increases as a result.

The DC source center in Figure 2 provides an enclosure where the battery, wind turbine, and inverter connections to the DC bus can be properly fused and safely interconnected. Three parallel strings of eight Trojan (Santa Fe Springs, California) L-16 batteries are used for energy storage. The Trojan L-16 is a 6-volt flooded lead-acid battery, with a nominal 350 amp-hour capacity at a discharge rate of C/24 (i.e., the total battery capacity is discharged over a period of 24 hours). Because discharge rates used in the system are appreciably higher, the real battery capacity is about 300 amp-hours, which corresponds to about 43 kW-hrs of energy storage. For the peak season daily load without the RO system of 46 kWh, this corresponds to about 14 hours of storage if the batteries are discharged to 60% depth of discharge. For the peak season daily load with the RO system the diesel is estimated to run about 4-6 hours per day, hence battery storage duration will vary depending on diesel run time.

The existing diesel in the system uses a three-phase generator. Although a three-phase RO system that would be compatible with the diesel could have been purchased, this would have required a three-phase inverter if the RO system was to ever be run off of the renewable system. A three-phase inverter is significantly more costly than the two single phase inverters and was outside of the project budget, hence a single phase RO system at 240 volts was purchased. This could be powered by the two inverters or the three-phase diesel using only two phases of the diesel distribution system. (The three-phase diesel current would be 120 degrees out of phase and the RO motor would like to see a 180 degree phase angle because it's single phase at 240-volts, but this was not a concern as it would only lower the efficiency of the motor a little and would not significantly affect diesel fuel consumption).

Because of the presence of both 120- and 240-volt loads (i.e., the RO system), two 120-volt Trace (Arlington, Washington) inverters were "stacked" together to provide power at both voltages. Using two 5.5 kW inverters together doubled the total inverter capacity to 11.0 kW and also doubled the surge or start-up capability of the inverters. The electrical surge requirement for the RO machine was estimated

based on the locked rotor torque of the motor and was very close to the combined surge power rating of the two inverters, so close that it was impossible to discern without testing if the inverters could start the RO system without the diesel. Because the system start-up could not be tested before installation, it was decided to install the RO system and use the diesel to start it in parallel with the inverters if the inverters could not start it alone. However, because the diesel is three phase and the inverters are single phase, parallel operation would require rewinding the diesel to have two phases which would be 180 degrees out of phase and hence be compatible with the inverters which are 180 degrees out of phase.

In summary, the approach to integrating the single phase 240-volt RO load into the three phase diesel system without first being able to test the inverters during RO startup was to 1) try a switched system whereby either the diesel or the inverters power the RO load, providing the inverters can start the system, and if the inverters could not start the RO then, 2) rewind the diesel for two-phase operation so that the inverters could run in parallel with it and the diesel could start the RO and then let the inverters power it after it is started.

Because of the high energy requirements for the RO desalination system, it was not intended to run the RO system extensively from the inverter system during high water demand months with no rain (rainwater will still be collected during the rainy season for water supply). This is primarily because the battery bank is undersized to continually cycle all the energy required to power the RO (a cost constraint from the project and a drawback to RO systems). (Future improvements in energy requirements [i.e., kWh/liter] for small-scale water desalination systems could significantly reduce the costs of renewable energy desalination systems.)

SYSTEM INSTALLATION

The system was installed during a rainy, four-day period in October 1996. Two of the days were dedicated to rewiring the AC load center, as the previous load center was wired poorly and several short circuits occurred. Installation time for the wind turbine system was two days. The concrete for the wind turbine tower anchors was poured several weeks prior to allow for it to dry completely.

Tower and wind turbine assembly was easy because the system was installed on the ground and tilted up. The use of a tractor simplified installation significantly, as it was used to move large parts (e.g., tower sections and the wind turbine rotor) as well as to actually raise the tilt-up tower by pulling it up via a winch and gin-pole assembly. Bergey Windpower engineered a custom, integrated battery rack/DC source center whereby the batteries were housed on a rack, and the back side of the rack was used to mount the two inverters, DC source center, and wind turbine controller. This simplified the installation and wiring of these components and minimized the space requirements for the equipment.

SYSTEM MONITORING AND INITIAL PERFORMANCE RESULTS

A data acquisition system was installed in February 1997 to monitor performance of the system. The system consists of a tower mounted anemometer and wind direction sensor, transducers for measuring DC current from the wind turbine and DC current to the batteries and to the inverter, DC bus voltage, battery temperature, AC watts and power factor, and diesel on/off status.

To date the system has been characterized by low loads. This is because the RO system is not in use yet and because the system was designed for 20% higher loads to allow for future load growth. In addition, the icemaking load is lower than originally estimated because the owner has decided not to sell ice. The RO system was not ready for operation during the commissioning of the renewable energy system. Months after commissioning of the renewable energy system, the RO system was installed by the owner, but it was damaged during its installation and has yet to be repaired; hence, the RO system has not been powered to date.

Figure 3 shows the hourly turbine output during May. Much of the energy is dumped because the load is small (the average load for April/May is 1.1 kW as compared to the estimated future load shown in Figure 1) and the batteries are charged above the high-voltage cut-off much of the time, so the turbine charge controller limits the current to the batteries (this can be seen by the points on the graph below the top of the power curve).

Average inverter efficiency from March through June is about 80%. Although the loads are well below rated inverter capacity, the inverter efficiency does not drop at the lower loads. The battery charging efficiency is about 63% for the same time period, which is low, primarily because the batteries spend much of their time between 85% and 100% state-of-charge (SOC) due to the low loads. Continuous battery charging at high SOC is very inefficient because of the battery's inability to accept as much current compared to a lower SOC (below 80% SOC is where efficient battery charging occurs, but batteries are given an equalize charge every month to prevent premature aging). Based on the above efficiencies, the combined battery/inverter efficiency for energy cycled through the batteries is about 50%, which is low. Of course energy produced from the wind turbine will go directly towards meeting the load when loads are present and hence not be subject to battery losses. Therefore, better load management, i.e., more load during high winds, would improve overall system efficiency because it would use more of the wind energy directly without cycling it through the batteries. In addition, a higher overall load on the system would result in more efficient battery charging because the batteries would be cycled below 80% SOC more often.

Figure 4 shows the power output of the turbine for one second averages and no current regulation (i.e., voltages below the high voltage set point for current regulation). There is little data above about 14 m/s, which is the wind speed that corresponds to rated power, so maximum power output cannot be determined; however, it appears that wind turbine power would reach about 7 kW at rated wind speed. (Note that this data should not be compared to published power curve data because it was taken at 1 hertz, and the anemometer is tower-mounted below the turbine; however, it is typical of field installation data where an approximate indication of power output is useful.) The data logger will be reprogrammed in the future to record one-minute average data of turbine power output.

The wind system has supplied more than 95% of the resort's energy since installation. The diesel was started a total of 22 times during the months of March through June for 162 hours of run-time, which is 5.5% of the time. Twelve of these starts occurred during the beginning of June, which was a low-wind resource period.

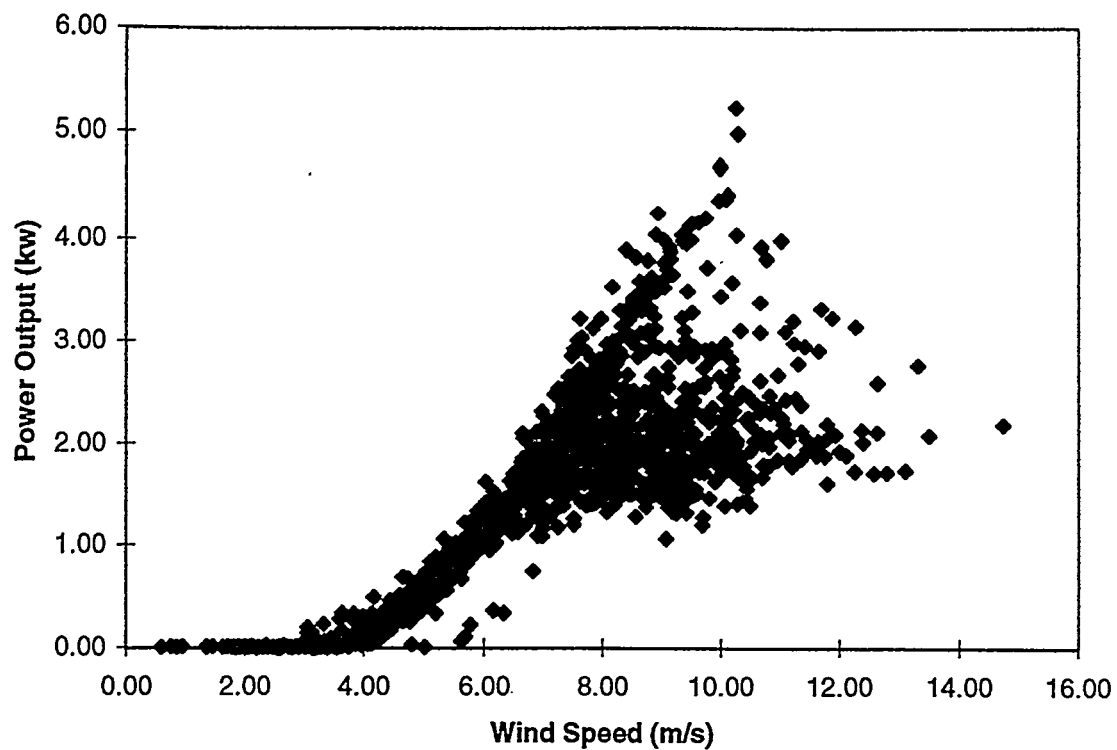


FIGURE 3. TURBINE POWER VERSUS WIND SPEED
10 MINUTE AVERAGE WITH VOLTAGE REGULATION

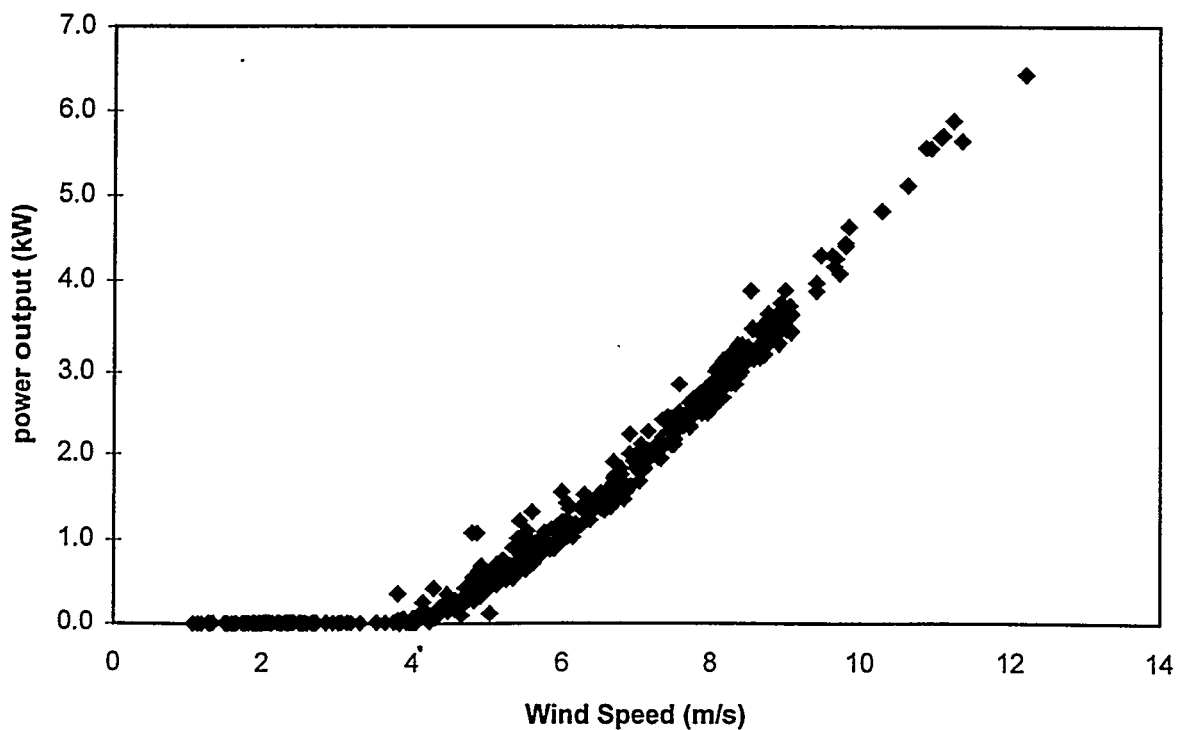


FIGURE 4. ONE SECOND POWER OUTPUT WITHOUT VOLTAGE REGULATION

OPERATIONS AND MAINTENANCE

Providing for good future O&M support is a key part of any remote power system program. In this case, Bergey Windpower trained the owner of the system, who is technically capable of system maintenance, as a first step in system diagnosis and maintenance. Should a problem arise and the owner could not fix the system, Bergey Windpower offered a three-year warranty on the system. A lack of a local technician/wind turbine representative in the area made a local three-year maintenance contract difficult, although in many installations this is a preferred alternative.

LESSONS LEARNED

The design, bidding, installation and commissioning of the system resulted in several useful "lessons learned." Turbine noise has been a small problem with some of the guests staying at the resort, and future installations should take note of this and locate the turbine farther away from residences (greater than 50 meters is a rule of thumb). The 48-volt winding required that the turbine be located close to the DC source center, but since the 48-volt winding does not seem to result in a higher power output, there is no reason to locate the turbine so close to the DC source center in future installations. Significant problems occurred with the existing diesel after system commissioning, but none of these problems were related to the renewable energy system. Because of the low cost of a new diesel, future installations should consider purchase of a new diesel.

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Status and Modeling Improvements of Hybrid Wind/PV/Diesel Power Systems for Brazilian Applications

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ABSTRACT

This paper presents a summary of the ongoing work on the modeling and system design of hybrid wind/PV/diesel systems for two different sites (Joanes and Campinas) in the Amazonia region of Brazil. The work incorporates the latest resource data and is based on the use of the Hybrid2 simulation code developed by the University of Massachusetts and NREL. Details of the baseline operating hybrid systems are reviewed, and the results of the latest detailed hybrid system evaluation for each site are summarized. Based on the system modeling results, separate recommendations for system modification and improvements are made.

INTRODUCTION

Brazil is actively supporting a renewable energy development program, with a major emphasis on PV and windpower projects (1, 2). A key part of this program involves the development and installation of hybrid power systems for rural applications. A U.S. Brazil Rural Electrification project has been established to implement a joint research and technology demonstration pilot project in several northern Brazilian states. This project is managed by the National Renewable Energy Laboratory (NREL) in conjunction with the Brazilian Center for Electric Energy Research (CEPEL) and the Brazilian state utilities.

In the region of the Amazon Basin (Amazonia), many places are accessible only by boat. Approximately 300 villages in this region have autonomous diesel electric generators, that often provide electric service for only a few hours each day due to the high cost of delivered diesel fuel and maintenance problems. Renewable energy hybrid (wind/PV/battery/diesel) power systems are of great interest to the state utilities and to Eletrobras (the main federal utility) as a method of enhancing electric services in Amazonia while reducing the diesel fuel consumption, and the associated cost of fuel. Today, electricity cost in these villages is subsidized by the rest of the Brazilian population at approximately \$250 million per year (1). The demonstration of viable hybrid power system operation in these remote regions could open up a significant near-term market for renewable hybrid power systems.

Under NREL support, two hybrid power systems have been installed in Amazonia, at the villages of Joanes and Campinas. As a part of this project, the University of Massachusetts, under subcontract to NREL, has provided analytical support in the areas of: 1) Hybrid system case studies modeling; 2) Comparison of models with field test data; and 3) System design improvements. The initial emphasis (3, 4) was in the area of system modeling, and this paper represents an extension of this work. Due to a lack of experimental data, this paper will concentrate on modeling improvements, detailed system modeling, and preliminary recommendations for system improvements.

DESCRIPTION OF HYBRID SYSTEMS

As shown schematically in Figures 1 and 2, the overall details of the two systems, including their initial baseline designs, are summarized below. It should be noted that the designs of the systems are significantly different. In its initial baseline configuration, the Joanes hybrid system will operate in a peak shaving mode, transferring the demand of the village to off peak periods at the diesel generation plant (in Salvaterra). In this way, it is expected that the maximum energy available from renewable sources will be used. The main objective of Joanes hybrid system is to introduce a new technology for Brazilian rural electrification. In Joanes, the renewable energy generation was expected to reach 115 MWh/year or about 45% of the present total demand on a yearly basis. A concurrent program for energy conservation in the village is expected to boost the fraction of load met by renewables to over 60%. The Campinas design, a retrofit hybrid system, is designed to meet the entire load requirement with an autonomous PV/diesel system. It was also designed to increase the power availability while decreasing the fuel consumption.

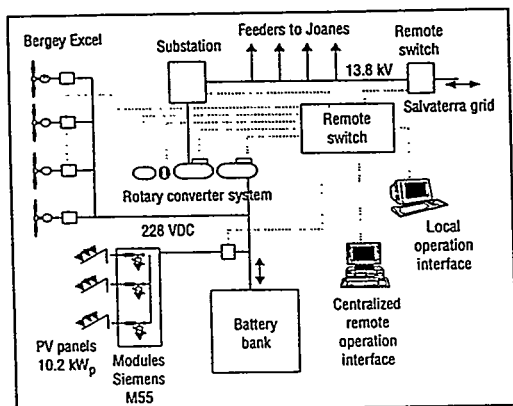


Fig. 1 Schematic of Joanes Hybrid System

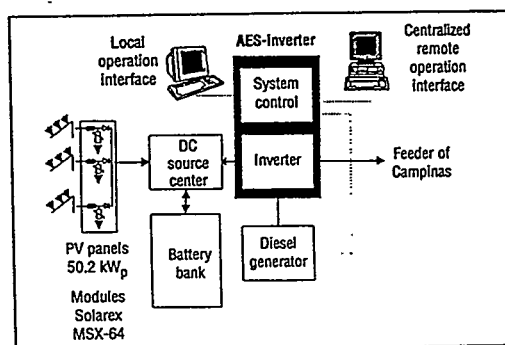


Fig. 2 Schematic of Campinas Hybrid System

A) Joanes

This system, a nominal 50 kW wind/PV/battery hybrid system is installed in the village of Joanes, located at the municipality of Salvaterra, on Marajo Island, state of Para. The Joanes village has a small grid with approximately 150 consumers and is conventionally powered by an autonomous diesel generation system located in the larger town of Salvaterra, 17 km north. The hybrid system is designed to be operated either independently or connected to the local grid. While in the interconnected mode, the Salvaterra diesel generator will charge the battery and meet the Joanes village load. It is expected that the grid-connected system will improve the power availability and decrease energy requirement from Salvaterra.

The system design and control, and the power-processor hardware were supplied by the New World Village Power Company of Vermont. This system is based on a rotary converter (shaft-coupled DC motor and synchronous alternator), rather than an electronic inverter, for power conversion. It is comprised of four 6 kW wind machines supplied by Bergey Windpower, 10.2 kW of M55 PV modules from Siemens Solar Industries, and 1000 Ah @ 228 VDC of Hoppecke batteries. As shown, the system is connected to the Salvaterra power plant, with a nominal capacity of 1.2 MVA, through a 17 km line operated at 13.8 kV.

B) Campinas

This hybrid system is an autonomous 50 kW PV/battery/diesel system installed in the village of Campinas, about 100 km upstream from Manaus, in the state of Amazonas, between the Solimoes and Negro rivers. Two existing diesel units, that currently supply the village load for a few hours a day, were modified to interface with the renewable sources and the battery through a bi-directional inverter. As originally planned, this system was to have the option for 20 kW of wind generation,

if the wind resource were adequate. The system controls and power processor were supplied by Advanced Energy Systems Limited (AES), as a subcontractor to the Bergey Windpower Corporation. A 50 kW (fixed) PV array was supplied by Solarex corporation. Control, data acquisition, fault detection, and diagnostics are primarily provided by the AES inverter's internal capabilities. A local operator interface is connected to the inverter via a serial link.

EVALUATION PROCEDURE- METHODOLOGY

Using the Hybrid2 code developed at the University of Massachusetts and NREL (5), a systematic design approach, described in a previous paper (3), was used to perform the systems analysis for the 2 Brazilian hybrid designs. Initially a set of preliminary configurations are defined. The relative merits of each configuration were determined by assessing the system behavior under variation of design variables that are incorporated in the Hybrid2 model (Parametric Analysis Definition). The design variables are grouped into controllable parameters (System Factors Assessment) and non-controllable parameters (External Factors Assessment). For example, controllable parameters to be investigated include component size, and system control strategy. Non controllable parameters include system economics, resource variability, and system loads. Some of these parameters may have a major effect on system performance.

Simulation results from Hybrid2 provide information on first and second order effects of parameter variations on the system energy flow and economics. Once those effects have been determined, the simulation and processed results allow one to establish the relationship among several design variables. Finally, a Feasible Region Criteria that incorporates key criteria elements is established so that the selected or recommended configurations are defined. A summary of results for the two systems follows.

APPLICATION OF EVALUATION PROCEDURE- JOANES

A) System Characterization

The evaluation procedure for Joanes was divided into preliminary and detailed phases. The preliminary one has been described previously (3). The detailed phase incorporates additional resources data and improvements on the system analysis (6). Details of this methodology are summarized in Fig. 3.

Additional resources data, based on 10 minute averages, have been acquired from CEPTEL and eleven months of data (May 1, 1994- March 31, 1995) have been used in the Hybrid2 modeling. In terms of system requirements, no detailed load assessment was available, so a simulated daily profile was assumed constant throughout the year, except for the month of July when the load expansion may experience 90% increase due to intensive tourist activity (7). The average daily energy demand is assumed to be about 740 kWh.

The baseline control strategy (8) reflects the main objective of the grid connected hybrid system which is to shift the Joanes peak load on Salvaterra to off peak hours. A Programmable Logic Controller (PLC) with user interface capabilities allows the operator to set the operation modes that define the energy flow of the system. The input parameters for the decision the operation mode are: time of day, Salvaterra grid status, battery state of charge and renewable energy availability. The main operation modes are:

- 1) Charge time: The Salvaterra Diesel Generation System (SDGS) charges the battery and meets the Joanes load.
- 2) Supply time: The hybrid power system meets the Joanes load. SDGS is disconnected.
- 3) Any time: If renewables are greater than conversion losses 'push' renewables to the grid otherwise renewables charge the battery.

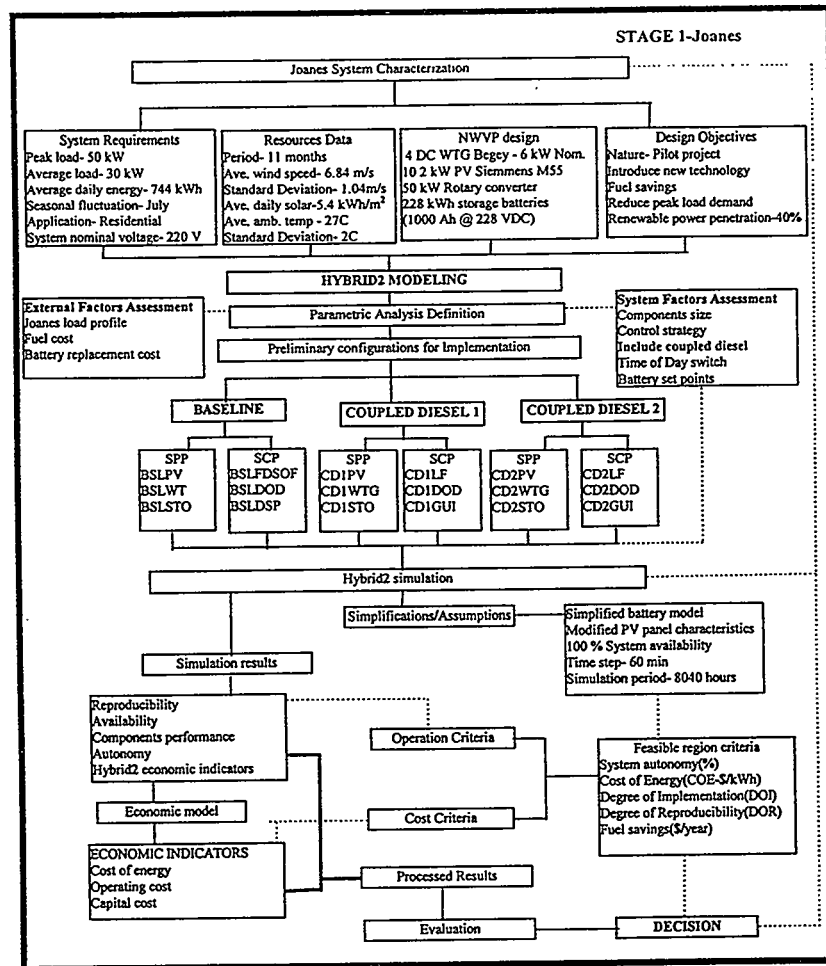


Fig. 3 Evaluation Procedure for Joanes System

B) Hybrid2 Modeling

The Salvaterra grid was represented by a 60 kW diesel on the AC bus. Since the actual diesel loading in Salvaterra is unknown, this information will provide information only in terms of energy requirements and the time needed to keep the Salvaterra switch closed. Other major assumptions included those required to simulate the Siemens M55 PV modules with a one-diode model. For the batteries, representative capacity and voltage curves were used for the KiBam submodel. For the control strategy, a potential major source of model variation, Table 1 gives the actual state transitions and the corresponding assumptions used in Hybrid2. It is not expected that a logistic simulation tool will be able to model a real time controller. The main difference, however, is in the renewable energy flow in the major operational modes. For instance, the push renewable energy to the grid, keeping the battery fully charged, is a situation that can not be modeled (this is equivalent to a peak shave and cycle charge in the same simulation). The same reasoning applies to the renewable energy input charging the battery with no energy flow to the AC bus. As shown, the load following and time of day switch was the control strategy defined in Hybrid2 to model the baseline configuration.

Following the previously described procedure, the configurations are labeled according to the nature of the parametric analysis (system factors assessment). For example, the configuration group BSLPV represents all configurations that use the baseline as reference and change only the photovoltaic size. The parametric variable (PRV) refers to the design parameter to be changed.

The preliminary configurations are: 1) Integrated rotary converter and coupled diesel-50 kW (CD1), 2) Integrated rotary converter and coupled diesel-100 kW (CD2). The configurations CD1 and CD2 present a different operation philosophy. That is, there is no time of day switch and two main control strategies have been defined, cycle charge and load following. For the integrated rotary converter cycle charge is consistent with the actual system operation which operates the coupled diesel as close as possible to the rated power charging the battery and meeting the load. The external factors assessment include load scale and variability variations. The renewable energy sources are also changed to reflected pattern changes during the system lifetime. The major economic parameters to be changed are the fuel cost and general inflation.

ACTUAL STATE TRANSITION	HYBRID2 ASSUMPTION	NATURE
1. OFF (Machines and renewable sources are shut down)	100% Availability	Optimistic
2. STAND BY (Machines are shut down and renewables charge bat.)	Diesel meets the net load (load-renewables). No energy goes to battery unless there is excess. The machines never shut down.	Relative
3. and 4. Spin-up and Sync B (Machines brought up to speed and synchronization)	Ditto	N/A
5. CHARGE BATTERY (Salvaterra/renewables charge the battery-90%SOC) Salvaterra meets the load	Boost charge. Salvaterra charges the battery and meets the net load (load-renewables).	Relative
6. LOAD RAMP (Grid switch is open)	Ditto	N/A
7. SUPPLY LOAD (HPS/Reconexables + batteries) supplies the load) Reconnect to Grid if: 1. Load > Battery + renewables 2. Battery SOC < 50%	Forced diesel shut off. 1. Unmet load 2. Unmet load	Conservative
8. DEAD-BUS SYNC If SOC is not operating HPS meets the load	It depends on the net load.	N/A
9. Sync A. AC machine brought into synchronization (Grid switch is closed)	Forced diesel shut off period is over. Diesel meets the net load.	N/A
OR		
2. STAND BY	10. PUSH RENEWABLE (If reconexables)	
10. PUSH RENEWABLE There is no change in the battery SOC	Hybrid2 natural behavior. The change in the bat. SOC may happen	N/A
11. X RAMP It ramps the power levels in transition between states 5, 10 or 2.		

Table 1 Comparison of Actual and Hybrid2 State Transitions for Joanes

C) Simulation Results

Table 2 summarizes a series of simulation runs for Joanes (the configurations are defined in Ref. 6). The renewable energy production based on the 8040 hour simulation period is 104 MWh/yr which represents about 40% of the yearly load demand. As should be expected, the inclusion of the coupled diesel does not change the fossil fuel energy requirement, since the renewable energy total remains the same. However, the system autonomy (defined as energy required - Salvaterra contribution/ energy required) is substantially improved. The fuel savings (based on estimated diesel fuel consumption curves), is about 15% for the baseline. The coupled diesel configuration using load following gives lower fuel displacement and efficiency. This is because there is no time of day switch, therefore the diesel is kept running all the time (the renewable energy is never able to meet the load and losses).

Configuration	Joanes load	PV	Wind	Salvaterra	Diesel	Fuel use	Fuel Efficiency	Hybrid System
	(kWh/year)	(kWh/year)	(kWh/year)	(kWh/year)	(kWh/year)	(l/year)	(kWh/l)	Autonomy(%)
Baseline	272,356	16,870	87,505	214,258	N/A	87,058	2.46*	21
Base case	272,356	N/A	N/A	272,356	N/A	102,086*	2.66*	0
Coupled Diesel 1	272,356	16,870	87,505	5,532	268,465	92,244	2.91	98
Coupled Diesel 2	272,356	16,870	87,505	0	289,416	144,916	1.99	100
CD1LF	272,356	16,870	87,505	5,532	216,862	125,424	1.73	98
CD2LFBC1	272,356	16,870	87,505	0	289,331	144,905	1.99	100
CD2LFBC2	272,356	16,870	87,505	0	289,337	144,907	1.99	100

Table 2 Simulation Results for Joanes

Figures 4 and 5 present a time series power flow for the load following case and the single coupled diesel, respectively. As shown in Figure 4, the battery storage (1000 Ah @ 50% DOD) is unlikely to carry the Joanes load for a period of 5 hours. Note that here the boost charge was not used, as was the case in the previous analysis (3). For this baseline configuration, an option

under current evaluation is increasing the DOD or storage size. Economic constraints may limit this option.

As shown in Figure 5, the power conversion and battery charging losses contribute to a higher fuel consumption for the CD1 case. Also, the battery charging losses appear to be high from the Hybrid2 simulation. It is expected, however, that actual data from the present installed system will give a better estimate for the battery charge/discharge losses.

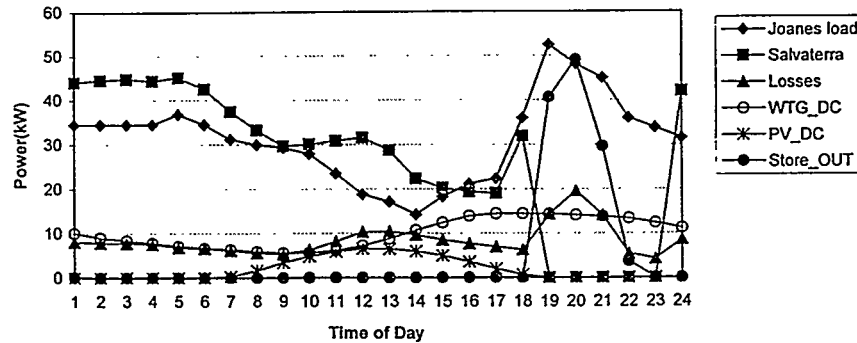


Fig. 4 Joanes Simulation Results: Load Following Design

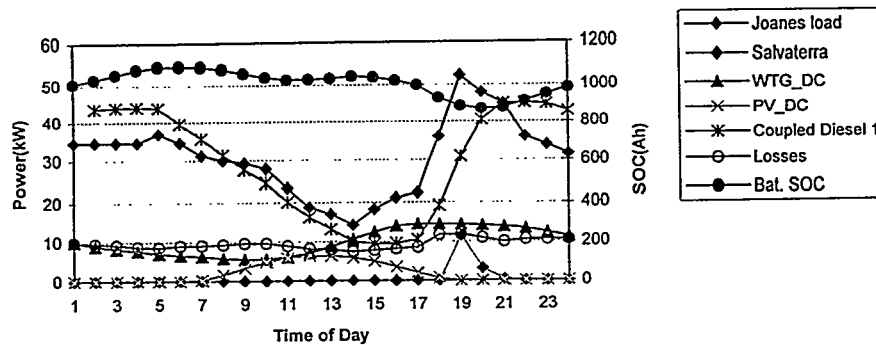


Fig. 5 Joanes Simulation Results: One Coupled Diesel Design (CD1)

D) Decision and Optimum Design

In terms of long term performance for the baseline configuration, it is possible to achieve a desired fuel displacement. It does not appear, however, that the hybrid system (DC sources and battery) operating in a peak shave mode by decreasing the peak load evening demand represents a significant improvement in terms of energy availability due to unreliable operation of the Salvaterra diesel. Even though the diesel requirement is essentially the same for the configurations CD1/CD2, the Salvaterra grid does not need to interact with the hybrid system and would be used only in a peak shave mode carrying the village load above the integrated rotary converter (including coupled diesel) system capacity. The configuration CD2 appears to be the most appropriate choice not only in terms of system autonomy, but also in the area of long term costs since it can better accommodate renewable energy and load expansion. This scenario does not require any interaction between Salvaterra and the hybrid system, thus decreasing the losses associated with the charge time (Alternator and DC machine).

The degree of model reproducibility is qualitative at this time, and a field data analysis is still required to assess the model accuracy. In terms of implementation, the CD1/CD2 configurations represent state-of-the-art for the supplier, and a low capital cost addition. Thus, based on these results, it appears that the coupled diesel is a better option on a technical basis using system autonomy as the main criteria. However, the effects of external and system factors still are under consideration before a final design selection is made.

APPLICATION OF EVALUATION PROCEDURE- CAMPINAS

A) System Characterization

The evaluation procedure for Campinas follows the same steps as were outlined in the previous case. However, the operation and system design philosophy were very different. That is, the hybrid system in Campinas is a retrofit to an existing dual diesel generation system, and the main goal of the Campinas HPS is to increase power availability and decrease fuel consumption from the existing dual diesel system. It is expected that the PV-diesel system may provide 24 hours period of electricity. The application of the evaluation procedure for Campinas is shown in Figure 6.

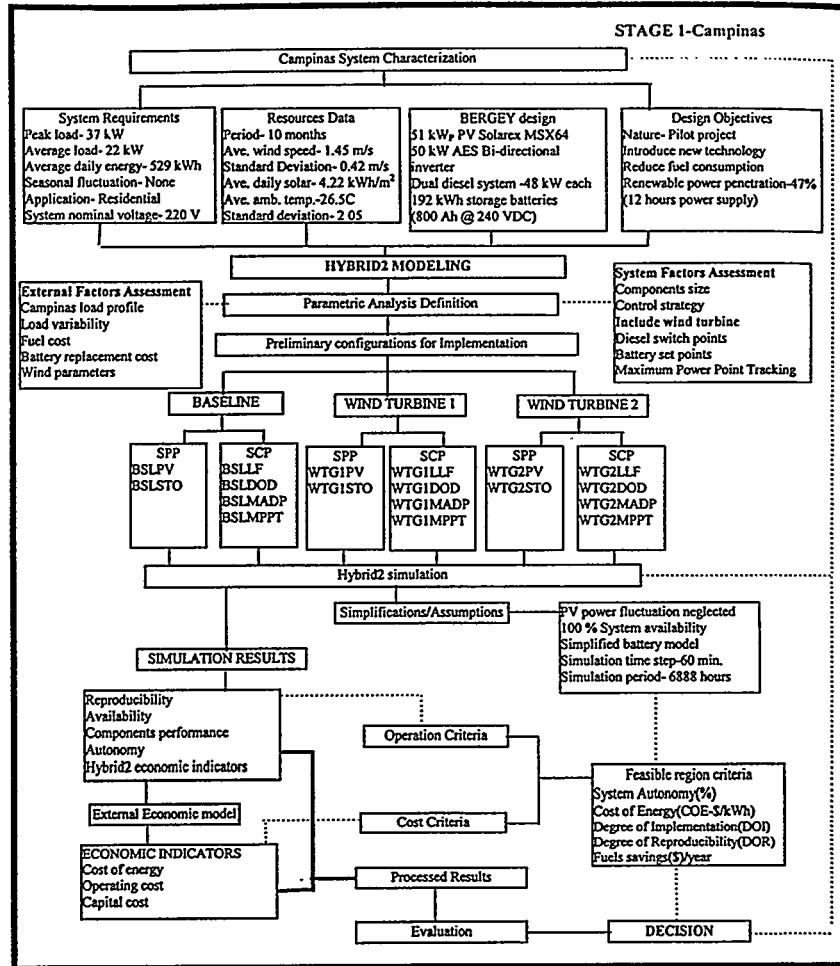


Fig. 6 Evaluation Procedure for Campinas System

As with the previous case, no detailed load data was available, and as shown in Figure 7, the load profile information differs from one source to another. The load profile used for the Hybrid2 modeling was determined by choosing the highest value from each source for each hour's time step. The resources data in Campinas village includes 10 months of data (Oct. 1, 1995 to July 31, 1996). Figure 8 presents a comparison of the Joanes and Campinas resource data.

The Campinas HPS incorporates a AES Static Power Pack (SPP) controller (9). The SPP is supposed to be fully automatic, and the system has two major operation modes:

- 1) Inverter-only mode: Low load operation period. The DC sources (Renewables + battery) meet the Campinas load and the diesels are shut down. If the battery SOC drops below 50% , the diesels are turned on.
- 2) Parallel operation mode(load sharing): High load operation period. The diesel and inverter (DC sources) operate in parallel.
- 3) Parallel operation mode(battery charging): Medium load operation period. As the battery level decreases and the diesel is on, the battery is charged by the bi-directional inverter and no power from DC sources is sent to AC bus. The diesel will vary the power to operate at high efficiency according to the allowable charge rate.

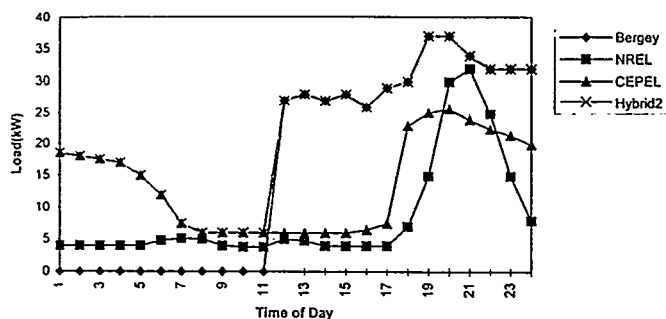


Fig. 7 Campinas Load Pattern

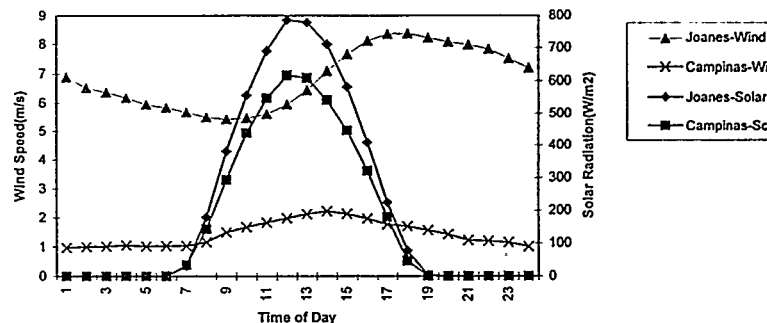


Fig. 8 Resource Availability

B) HYBRID2 Modeling

The Hybrid2 input parameters are the same as established for Joanes modeling except for the PV modules that use Solarex MSX-64 electrical characteristics and the bi-directional inverter (with an assumed conversion efficiency of 90%). The system information to establish the hybrid input parameters is given in Figure 6, which also show the various configurations, including wind turbines, that were simulated. The control strategy for the baseline configuration is based on load following. Table 3 presents the Hybrid2 assumptions for the major state transitions.

OPERATION MODE	HYBRID2 ASSUMPTION	NATURE
1. INVERTER MODE (Dual diesel system is shut down/Renewables+Batt. meet the load.)	Diesels are shut down if net load (load - renewables) is negative.	OK
2. PARALLEL MODE(Load sharing) (One diesel + Renewables/battery meet the load.)	Diesel meets the net load (load -renewables). The battery discharge depends on renewable energy level and load excursions above the diesel .rated power.	OK
3. PARALLEL MODE(Battery charging) If the diesel is on and the battery level is low (One diesel + Renewables charge the battery and meet the load.)	Diesel meets the net load (load -renewables) and battery is charged if there is enough renewable or load is below the minimum allowed diesel power.	Relative

Table 3 Comparison of Actual and Hybrid2 State Transitions for Campinas

The Campinas hybrid system allows an easy expansion of renewable components, with the main variation being the PV subcomponent and battery bank size. The inclusion of wind turbine generators was an alternative based on an estimate of the wind resource (10). In light of the latest wind data at the site, would probable not be considered for this particular hybrid system. The external factor assessment follows the same process as that established for Joanes. With regard to the control strategy the main parameters are the battery DOD and minimum allowed diesel power. Also, a number of preliminary configurations were established to assess the effects of wind turbine on system performance.

C) Simulation Results

Table 4 presents a series of simulation runs for Campinas. The PV yearly energy production (based on a 6888 hr simulation), is about 57 MWh/yr which represents about 30% of the yearly load demand. As shown the inclusion of wind turbines gives almost no contribution in terms of

energy availability and fuel displacement. The hard cycle control strategy for the Campinas system appears inadequate due to the high losses associated with the battery charging. With the load following strategy (considered for the baseline), a 20% fuel consumption can be achieved even though the battery use is not significant. The cycle charge (FPMRT, full power minimum run time) decreases the diesel operation time and increases the fuel efficiency with the penalty of a larger number of diesel starts and energy cycled through the battery

Configuration	Campinas load	PV	Wind	Total Diesel	Total Fuel Use	Fuel Efficiency	Diesel Op. Hours
	(kWh/year)	(kWh/year)	(kWh/year)	(kWh/year)	(l/year)	(kWh/l)	Annual
Baseline	192,903	56,608	N/A	152,634	65,572	2.33	7012
Base case	192,903	N/A	N/A	192,903	82,460	2.34	8760
WTG1	192,903	56,608	194	152,472	65,553	2.33	7017
WTG2	192,903	56,608	387	152,376	65,509	2.33	7012
BSLFPMRT	192,903	56,608	N/A	244,613	82,828	2.95	5673
WTG1FPMRT	192,903	56,608	194	243,914	82,570	2.95	5651
WTG2FPMRT	192,903	56,608	387	243,048	82,533	2.94	4474

Table 4 Simulation Results for Campinas

Figures 9 and 10 present the time series power flow for the FPMRT and the load following designs. As shown the PV contribution is small and the Hybrid2 time series results appear to reproduce the inverter and parallel (load sharing) modes. The PV energy input, however, is unable to meet the load and charge the battery. In this case, a boost charge is an option to be considered.

In Figure 10, the FPMRT design, the diesel power represents two diesels, and shows a large variation. This design decreases the diesel operation time and improves fuel efficiency under the penalty of a much higher number of diesel starts and energy cycled through the battery.

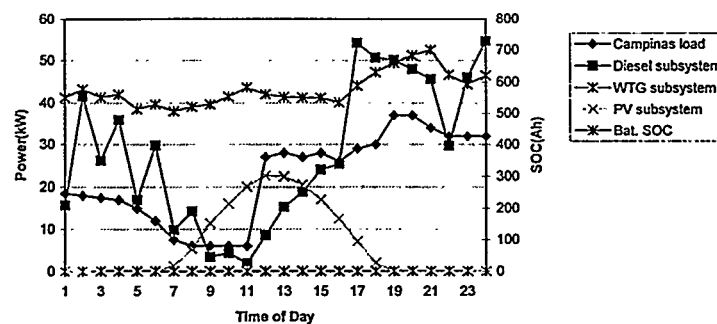


Fig. 9 Campinas Simulation Results: FPMRT Design

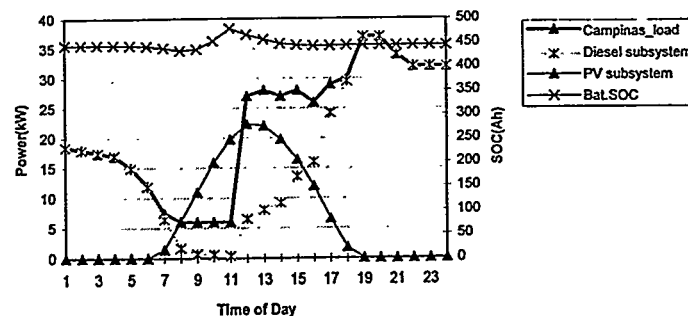


Fig. 10 Campinas Simulation Results: Load Following Design

D) Decision and Optimum Design

The degree of reproducibility appears to be higher for the Campinas hybrid system due to the nature of the parallel operation which is similar to the Hybrid2 behavior. The inclusion of wind generators is certainly an option not to be considered. That is, primarily due to the poor wind resource at Campinas, thus, the PV only system is the most optimum choice. With this type of system, potential areas for improvement include control strategy and expansion of PV panels and storage size.

SUMMARY/ PRELIMINARY RECOMMENDATIONS

The two hybrid systems studied here represent an important source of information for future hybrid system model development, and for the performance comparison of different system design options. At this point, recommendations have been made based only on the results of the modeling studies and no conclusive recommendations on the configurations to be implemented can be made until data from the initial field tests is evaluated, economic studies have been performed, and discussions with the institutions involved have been carried out.

For the Joanes system, a integrated rotary converter with a coupled 100 kW diesel (CD2) appears to be the most appropriate choice. The baseline configuration presents little benefits in terms of energy availability improvement, especially if the reliability level of the Salvaterra diesel generation system is considered. Also, the configuration CD2 can accommodate renewable energy sources and load expansion. The Campinas hybrid system presents a different system philosophy, and there are also areas for improvement. The inclusion of 2 additional wind turbine generators does not appears to be cost effective.

In order to assess the relative merits of the configurations presented in this work further, modeling will be pursued following the parametric analysis. Also, the Hybrid2 code should be modified to allow time of day specifications of control strategies (or contingent control strategies). In addition, completion of the field data analysis will provide information for a quantitative analysis .

ACKNOWLEDGMENT

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SIZING WIND/PHOTOVOLTAIC HYBRIDS FOR HOUSEHOLDS IN INNER MONGOLIA

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ABSTRACT

Approximately 140,000 wind turbines currently provide electricity to about one-third of the non-grid-connected households in Inner Mongolia. However, these households often suffer from a lack of power during the low-wind summer months. This report describes an analysis of hybrid wind/photovoltaic (PV) systems for such households. The sizing of the major components is based on a subjective trade-off between the cost of the system and the percent unmet load, as determined by the Hybrid2 software in conjunction with a simplified time-series model. Actual resource data (wind speed and solar radiation) from the region are processed so as to best represent the scenarios of interest. Small wind turbines of both Chinese and U.S. manufacture are considered in the designs. The results indicate that combinations of wind and PV are more cost-effective than either one alone, and that the relative amount of PV in the design increases as the acceptable unmet load decreases and as the average wind speed decreases.

1. INTRODUCTION

There are more wind turbines installed in Inner Mongolia, China, than in any other region of the world. These 140,000 wind turbines, in conjunction with low-cost batteries, provide electricity to about one-third of the non-grid-connected households in this region. However, these households often suffer from a lack of power during the low-wind summer months. The addition of photovoltaic arrays (PV) could provide a more reliable source of rural electrification for these areas. This report details an analysis of hybrid wind/photovoltaic systems, using batteries but not using engine generators, for individual households in Inner Mongolia. The sizing of the major components – wind turbine generators (WTG), PV, and batteries – is based on a subjective trade-off between the cost of the system and the percent unmet load. Two models are used to delineate this trade-off: (1) the simplified time-series model of Barley and Winn (Barley 1996a, 1996b; Barley and Winn 1996) is used to determine designs that are approximately least-cost for various levels of unmet load; (2) the more sophisticated Hybrid2 model (Green and Manwell 1995) is then used to more accurately determine the performance (unmet load) and cost of energy in each of these designs. For these computations, actual resource data (wind speed and solar radiation) from the region are processed so as to best represent the scenarios of interest. Small wind turbines of both Chinese and U.S. manufacture are considered in the designs. The results indicate that combinations of wind and PV are more cost-effective than either one alone, and that the relative amount of PV in the design increases as the acceptable unmet load decreases and as the average wind speed decreases.

2. RESOURCE ASSESSMENT

The models used in this analysis require hourly values of wind speed and solar radiation, preferably for a period of one year, so as to capture seasonal effects, diurnal cycles, storm cycles, and stochastic variations. For this project, monthly wind speed distributions at a 10 m hub height were provided for two scenarios (tentative specifications of the wind and solar resources). The corresponding average wind speeds and best fits to a two-parameter Weibull distribution are shown in Table 1. (v_c is the wind speed normalizing factor, and k is the shape factor in the Weibull wind

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speed distribution; see Eggleston and Stoddard 1987.) In addition, a set of data measured at three-hour intervals was obtained for nearby Jurh, for the years 1977-1979. In order to combine the weather *pattern* information contained in the three-hour data with the more site-specific *magnitude* information contained in the monthly distributions, the following procedure was used:

- Hourly data were generated from the three-hourly data using the method of linear interpolation between bracketing values.
- These hourly data were then scaled to match the annual average derived from the wind speed distribution for each scenario.

Table 1. Summary of Wind Speed Data, Measured at 10 m

Site	Elevation (m)	Average Wind Speed (m/s)	v_c (m/s)	k
Scenario A	900	4.9	5.2	1.7
Scenario B		3.6	3.7	1.4
Jurh, 1977	1280	6.0	~6.6	~2.2
Jurh, 1978		5.8		
Jurh, 1979		5.9		

(Note: v_c and k are parameters of the Weibull wind speed distribution; see text for reference.)

In remote areas, it is common for average measured wind speeds to decrease as a function of time (Schwartz and Elliott 1995). This may be due to lack of proper anemometer maintenance, construction of buildings near the anemometers, or the growth of trees near the anemometers. It is evident in Table 1 that the three-hour Jurh data indicate a stronger resource than do the (more site-specific) monthly data for the two scenarios. Thus the wind speeds used in these computations – 3.6 and 4.9 m/s – may be considered conservative estimates of the wind resource for the two scenarios. The seasonal profile of the wind energy produced by one WTG (model FD200) in Scenario A is shown in Figure 1.

Solar radiation data were provided in two forms:

- Profile data: Hourly global horizontal insolation was provided for a typical day and a peak day in each month. A data set of 8760 hourly

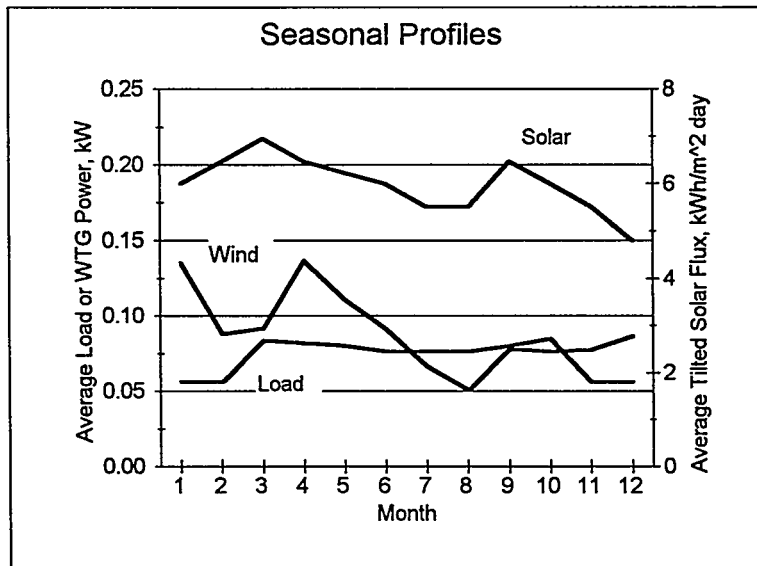


Figure 1. Seasonal profiles for the load, wind power, and solar power (Scenario A)

values was constructed by repeating the typical day profile for each day of each month. This method yields averages of 4.92 kWh/m²·day on a horizontal surface and 6.54 kWh/m²·day on the tilted surface.

- Daily data: Daily global horizontal insolation was provided for an entire year. A data set of 8760 hourly values was constructed by assuming a smooth, symmetrical profile within each day (per Duffie and Beckman, 1991, Sec. 2.13). This method yields averages of 4.61 kWh/m²·day on a horizontal surface and 5.99 kWh/m²·day on the tilted surface.

Of the two methods, the daily data set is selected for the computations reported in this paper. The advantages of using this data set are (1) correct total radiation for each month, (2) correct day-to-day variations, and (3) correct day-to-day correspondence of horizontal radiation with sun's seasonal position (used in conversion to the tilted surface). The disadvantage is that weather patterns within the day (such as the occurrence of cloudiness in the morning or the afternoon) are not represented. The daily data set is also the more conservative estimate of the solar resource. The seasonal profile of the monthly average solar radiation on the tilted surface is shown in Figure 1.

3. LOAD ASSESSMENT

A survey of current household loads in Inner Mongolia shows two general levels of electricity consumption: *high demand* households average 1075 kWh/yr and *low demand* households average 166 kWh/yr. In these analyses, a *medium demand* household of 633 kWh/yr is also modeled. The high demand households generally have a continuous refrigerator load and may also have washing and drying machines, while the low demand household is assumed not to include a continuous load such as a refrigerator. A household load profile was derived from a community load in Inner Mongolia of 51 households which is currently served by a wind/diesel system. We scaled this profile to 166, 633, and 1075 kWh/yr for the low, medium, and high demand households, respectively. The high and medium demand household loads were assumed to include refrigeration during the warmer months. The results presented in this paper are for the medium load of 633 kWh/yr. The hourly profile of this load is shown in Figure 2, and the seasonal profile in Figure 1. Unmet load typically occurs in the summer months of August and early September.

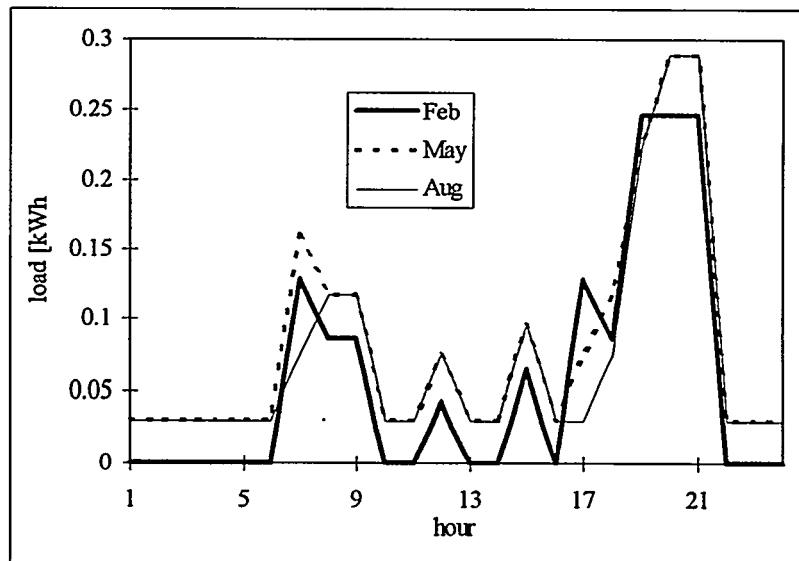


Figure 2. Household load profile used in the analysis

4. COMPONENT SPECIFICATIONS

The wind turbines modeled in this analysis include four Chinese turbines, three U.S. turbines and one German turbine. The annual output for each wind turbine in the Scenario A wind resource is listed in Table 2. The lower turbine outputs due to the lower air densities found at these altitudes are taken into account in this calculation. The most cost-effective turbines, in terms of total installed

cost per annual output, are the Chinese 200 W and 2 kW turbines. The Chinese turbines tend to have low hub heights (less than 10 m) and have been designed to accommodate the low wind speeds found at these heights. Figure 3 compares the power curves, normalized to the peak power for each turbine, of the turbines listed in Table 2. The Chinese power curves tend to rise more rapidly so that power can be generated at the low wind speeds which are found at the low hub heights of 6-10 m. Results presented in this paper are for the FD200 and Air 300 models; as shown in Table 2, these are the most cost-effective models of Chinese and U.S. manufacture, respectively, in the size range that matches the household load.

Table 2. Comparison of Small Wind Turbines from China, the United States, and Germany, in Scenario A [Byrne 1996b]

Turbine	Peak Power [W]	Hub Height [m]	Rotor Diam. [m]	Annual Output [kWh]	Total Installed Cost [\$]	Total Installed Cost per Annual Output [\$/kWh]
<i>China</i>						
Shangdu Livestock Machinery Works (SLMW)						
FD1.5-100	180	5.0	1.5	460	241	0.52
FD200	290	6.0	2.5	730	362	0.50
FD300	480	7.0	2.5	860	518	0.60
FD5.6-2000	2800	8.5	5.6	7000	2891	0.41
<i>United States</i>						
Air 300	380	6.0	1.1	280	542	1.94
BWC 850	1050	26.0	2.4	1690	3930	2.33
BWC 1500	1700	24.0	3.0	2750	8184	2.98
<i>German</i>						
German Wenus 5kW	6200	12.0	6.0	8900		

(Note that the Chinese tend to rate their turbines much more conservatively than is done internationally.)

The photovoltaic modules are assumed to be of 50 watts rated power, with an installed cost of \$321.50 and a service life of 20 years, and mounted at a slope of 44 degrees (equal to the latitude). The inverter is assumed to be rated at 575 W, with an installed cost of \$440 dollars and a service life of 10 years. The batteries (of Chinese manufacture) are assumed to have a charge capacity of 1.26 kWh, a service life of 150 equivalent full cycles, and an installed cost of \$142 each.

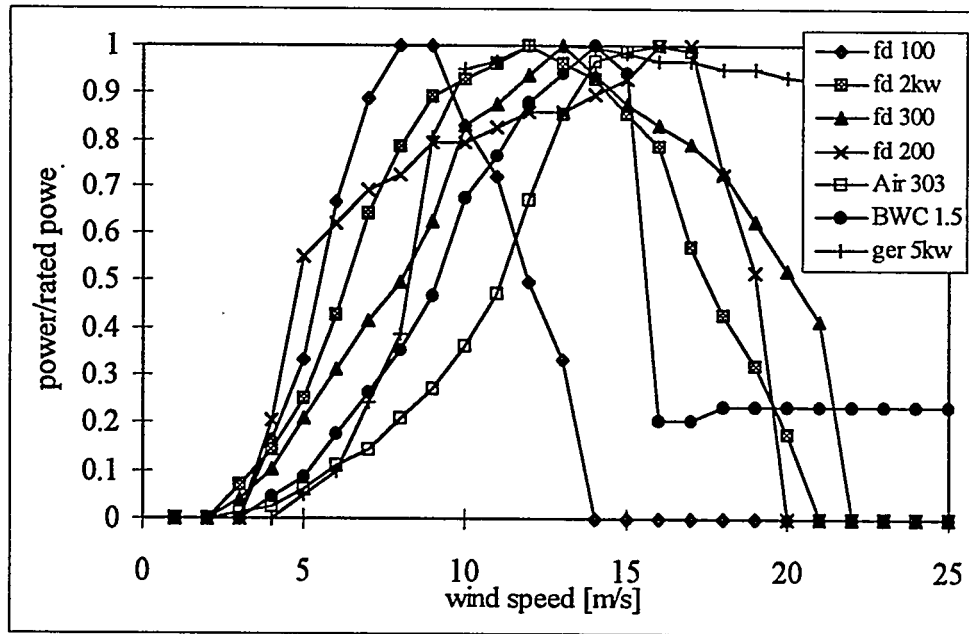


Figure 3. Comparison of scaled power curves from small wind turbines manufactured in China, the United States and Germany (Note that the turbines from China are designed for the lower wind speeds that are present at low hub heights.)

5. MODELING AND OPTIMIZATION PROCEDURE

In hybrid systems that feature an engine generator, the usual approach to optimization of the design is to minimize the life-cycle cost (LCC), which includes both equipment costs and fuel costs. In hybrid systems that do *not* feature an engine generator, there is no fuel expense involved. Instead, it is typical that a portion of the load will go unmet. Meeting 100% of the load with renewables and batteries would require an investment in the equipment needed to generate and store enough energy to withstand the longest doldrums (calm/cloudy weather); such equipment is excessive most of the time. In many cases, such an investment is not justified. Thus the component sizing problem involves a trade-off between the system cost and the unmet load (UL). If there is a definite economic cost associated with unmet load, a least-cost design can be determined mathematically. Otherwise, the trade-off between cost and unmet load is subjective. The following procedure is used here in determining optimal designs:

- Assign an arbitrary cost to unmet load, C_{UL} , in \$/kWh.
- Define the augmented life-cycle cost (LCC_{aug}) as the sum of the equipment costs, O&M costs, and unmet load cost.
- Size the components to minimize LCC_{aug} .
- Repeat steps a through c for various values of C_{UL} , plotting the results. (Higher values of C_{UL} drive the optimization to higher equipment costs and lower unmet loads.)
- Make a subjective judgement of the most appropriate design.

Two different models are used to perform these computations. First, a simplified, quasi-steady-state time-series model (Barley 1996a, 1996b; Barley and Winn 1996) is used to determine approximate least-cost designs. This model has the advantage of fast computation time and an efficient search algorithm for determining the least-cost component sizing (numbers of WTG, PV modules, and batteries) in step c above. Then the more detailed, stochastic model Hybrid2 (Green and Manwell 1995) is used to more accurately determine the cost of energy (COE) and unmet load for each of the designs indicated by the simple model. In this analysis, the COE is defined as:

$$\text{COE} = \text{LCC} \times F_L / (\text{Load} - \text{Unmet load}) \quad (1)$$

where:

COE = Cost of energy, \$/kWh
LCC = Life-cycle cost, present worth dollars (not including C_{UL})
 F_L = Levelizing factor, which converts a present worth to a uniform annual expense (based on a 20 year system life and a 12% discount rate)
Load = Household load, kWh/yr
Unmet load = Load that cannot be met by the system, kWh/yr

6. RESULTS

The procedure outlined above (steps a-d) has yielded the series of design options plotted in Figures 4-6, for the following cases:

Figure 4: Scenario A (average wind speed = 4.9 m/s), with the Chinese FD200 WTG.

Figure 5: Scenario B (average wind speed = 3.6 m/s), with the Chinese FD200 WTG.

Figure 6: Scenario A (average wind speed = 4.9 m/s), with the Southwest Air 300 WTG.

Each point on these graphs represents a design which has been determined as approximately least-cost for the corresponding level of unmet load. The graphs clearly illustrate the trade-off between COE and unmet load. In these results, the calculated COE values are higher than values calculated for existing systems in Inner Mongolia [Byrne *et al.* 1996a], partly due to the use of higher priced system components, and partly due to the fact that excess energy in this analysis is not utilized and is considered to have zero value.

Case	Wind (W)	Solar (W)	Battery (kWh)
A	400	0	1.26
B	400	0	2.52
C	400	50	3.78
D	400	50	6.30
E	400	150	6.30
F	400	200	7.56

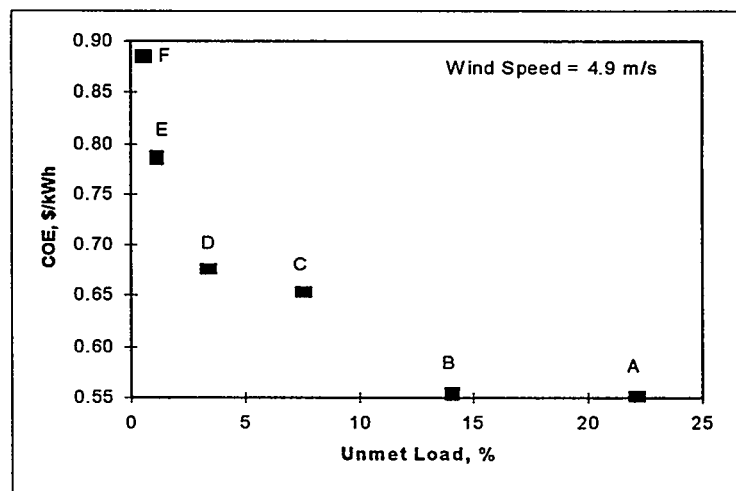


Figure 4. Results for Scenario A, with the Chinese FD200 WTG

Case	Wind (W)	Solar (W)	Battery (kWh)
G	400	100	2.52
H	400	150	3.78
I	400	250	3.78
J	400	250	5.04
K	400	250	6.30
L	200	350	6.30

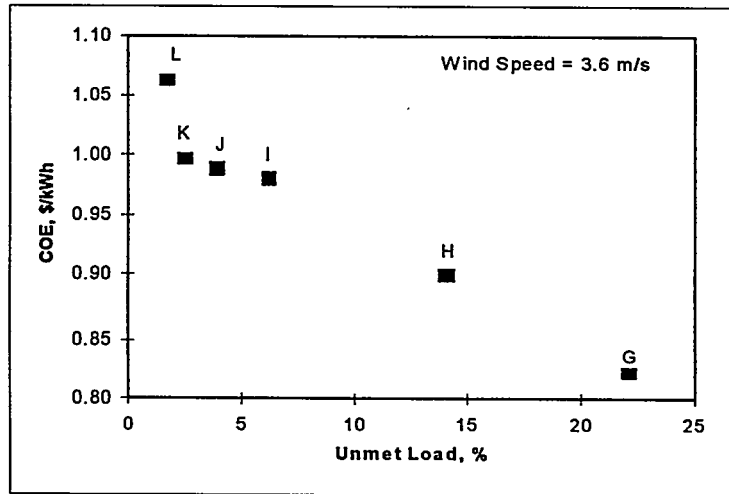


Figure 5. Results for Scenario B, with the Chinese FD200 WTG

Case	Wind (W)	Solar (W)	Battery (kWh)
M	300	250	2.52
N	300	300	3.78
O	300	350	5.04
P	300	350	6.30
Q	300	400	5.04
R	300	400	6.30

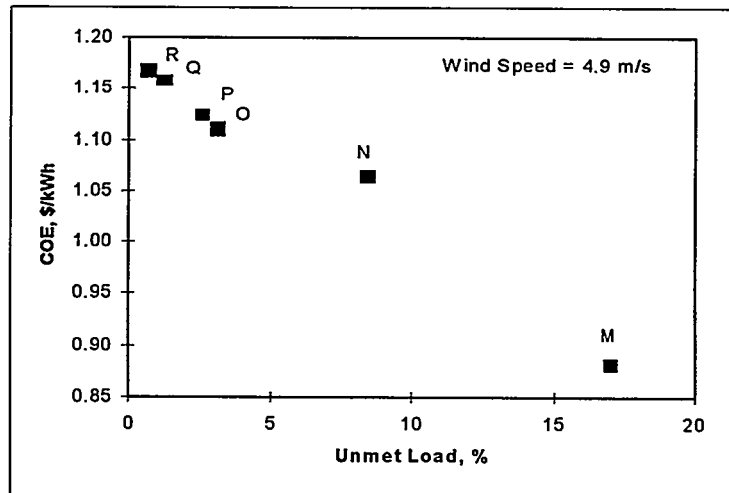


Figure 6. Results for Scenario A, with the Southwest Air 300 WTG.

The addition of PV helps to meet demand during the low wind summer months for a low incremental cost of energy. Due to the large uncertainties in the wind resource, computations for Scenario A were performed for both 4.9 m/s and 6.0 m/s average wind speeds. This illustrates the effect of estimating the resource incorrectly or of large interannual variations in the wind resource. The effect of this increase in wind speed on the wind-only systems is to reduce the unmet load by a factor of four. Reliability remains a problem in the summer months. The increased wind speed reduces the unmet load by a factor of 8 for selected wind/PV hybrids. Note that while the resource has a large effect on the amount of unmet load, it has little effect on the COE. For the case of 300 W wind, 200 W PV and 8.4 kWh batteries in the 6.0 m/s average winds (not shown in Figures 4-6), a large amount of excess energy would be generated. This energy could be used for optional loads such

as a water pump or heating element; however, to simplify this analysis, it has been assumed that excess energy is not utilized. In the 4.9 m/s average winds, this configuration is capable of generating about 870 kWh wind power and 460 kWh solar power, 520 kWh of which would be excess energy.

Larger amounts of PV are indicated for household systems in Scenario B due to the poor wind resource. It is likely that wind resource variation will have a lesser effect on these systems. For the case of 200 W wind, 400 W PV and 8.4 kWh batteries (not shown in Figures 4-6), about 400 kWh of wind power and 850 kWh of solar power could be generated. Approximately 400 kWh of this generation would be of excess energy.

7. CONCLUSIONS

In the type of hybrid systems studied here, which do not include fueled engine generators to provide back-up power, alternative designs are compared based on unmet load as well as cost. The relative importance of these two criteria is a subjective judgement; thus we have presented our results so as to illustrate the trade-off and provide some options. The use of the two models (the fast, simplified model to search for least-cost designs, and the slower, more precise model to verify performance) worked well. Between the two models, differences in the prediction of unmet load are consistently less than 2.5 percentage points for the cases shown; larger differences in the cost of energy result from differences in the prediction of battery life, which is considered to be only an estimate even in the more sophisticated Hybrid2 model. Based on the component specifications that were provided, the Chinese wind turbines are much more cost-effective than those of U.S. manufacture, at the wind speeds considered. Because the seasonal profiles of the wind and solar resources are somewhat complementary in this region (i.e., months of higher solar resource correspond to some of the months of lower wind resource, as shown in Figure 1), combinations of wind and solar perform better than either wind or solar alone. Between cases B and D in Figure 4, for example, the addition of PV to the wind-only system (in conjunction with an increase of battery capacity) reduces the unmet load from 14% to 3.3%, with a cost increase of only 22%. The relative amount of PV in the indicated designs increases as the acceptable unmet load decreases and as the average wind speed decreases.

The greatest uncertainties in this analysis are the wind speed data and the battery data (price and cycle-life). Future work includes the design of wind/PV/battery/engine hybrid systems for villages in these regions.

8. ACKNOWLEDGMENTS

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Test Results for the Oasis 3C High Performance Water-Pumping Windmill

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Abstract

The WINDTech International, L.L.C. Oasis 3C, a 3 m diameter, high-performance water-pumping windmill, was tested at the DME Engineering Wind Test Site just south of Midland, Texas from August through December, 1996. This machine utilizes a 3:1 gearbox with rotating counterweights, similar to a conventional oilfield pumping unit, driven by a multibladed rotor. The rotating counterweight system balances most of the pumping loads and reduces gear loads and starting torque by a factor of at least two and often by a factor of four or more. The torque reduction substantially extends gear and bearing life, and reduces wind speeds required for starting by 30 to 50% or more.

The O3C was tested pumping from a quiescent fluid depth of 12.2 m (40 ft) from a 28.3 m (93 ft)-deep well, with additional pumping depth simulated using a pressure regulator valve system. A 9.53 cm (3.75 in.) diameter Harbison-Fischer seal-less single-acting piston pump was used to eliminate pump seal friction as a variable, and standard O3C stroke lengths of 30.5 and 15.2 cm (12 and 6 inches) were used. The regulator spring was set to give a maximum stroke rate of 33 strokes per minute. The water pumped was returned to the well after flowing through a settling tank. The tests were performed in accordance with AWEA WECS testing standards. Instrumentation provided 16 channels of data to accurately measure machine performance, including starting wind speeds, flow rates, O3C azimuth, tail furl angle, wind direction tracking errors, RPM, sucker rod loads, and other variables.

The most significant performance data is summarized herein. For most of these results, wind speed and flow discharge were measured each second and one-minute averages were recorded.

A mathematical model of machine performance was developed that fairly accurately predicts performance for each of three test conditions.

The results verify that the O3C is capable of pumping water at wind speeds from 30% to more than 50% lower than comparable un-counterbalanced units. Balancing allows the O3C to be set up more heavily loaded than conventional windmills without making the starting speed abnormally high. Without needing a pump with a leakhole to start, it retains full volumetric efficiency right down to the starting wind speed, resulting in much greater flow in low-wind-speed conditions. The math model indicates that it could pump up to 29,140 l/hr (7700 gal/hr) from a shallow well at maximum stroke rate, and could still start in winds of 3.3 m/s (7.29 mph). It also predicts the standard O3C could pump small amounts of water from depths as great as 305 m. (1000 ft) and still start in winds of less than 2.3 m/sec (5.1 mph) at sea level, standard conditions. The Oasis 3C is a robust machine with a high level of versatility.

Background

The current version of the American multiblade wind pump has been around since the early 1900's. Many have worked to improve on its performance, including the idea of counterbalancing. Enterprising farmers and ranchers have used chains or cables with pulleys and buckets of scrap metal or rocks to provide balancing, which is dangerous when the cables fray or the chains wear out, and difficult to lubricate. Others have used springs and complex mechanisms that never survived prototype operation or required excessive maintenance. The Oasis wind pumps utilize the technology of the oil-field pumpjack to provide an elegant, efficient, and robust counterbalance mechanism.

In the quest for low-wind operation, any wind pump can be set up with a small cylinder on a short stroke in a shallow well so that it is under-loaded and will start in low winds. The medium and high-wind

performance is thereby sacrificed; it pumps hardly any water compared to what it could pump at higher wind speeds.

The torque required to start a conventional wind pump may be three times the torque required for steady operationⁱ. The large starting torque is often overcome through the use of a leakhole. This is a small hole in the pump piston or valve that lets all the water in the drop pipe leak out when the machine stops running, so it will have a minimum load when the wind comes up again. This arrangement was analyzed by Lysenⁱⁱ. The machine will then start rotating at a lower wind speed, but no water will emerge until a minimum pumping RPM is reached. The corresponding volumetric losses range from 100% just before the minimum pumping RPM to about 47% at three times this RPM and down to 10% at 16 times this RPM. These are substantial losses. The Oasis 3 can start in low winds without sacrificing medium and high-wind performance and without any leakhole losses.

Test Objectives

The initial test objectives were to measure the actual water pumping performance of the O3C as a function of wind speed. Other tests and development were performed, but space does not permit their discussion here.

Because the machine is capable of starting in very low winds, it was critical that it possess good wind direction tracking characteristics for low winds, and this was a dominant design aspect. Low-wind tracking is not necessary on standard farm windmills because they are usually loaded so they are not capable of starting in such low winds.

Instrumentation

The O3C was mounted on a standard Dempster 2.5" x 3/16" angle tower with a hub height of 12.2 m (40 ft) on a slight rise with excellent wind exposure. A meteorological tower was erected 10.7 m (35 ft) upwind of the O3C for the prevailing southerly wind direction.

The pump used for these tests was a 9.53 cm (3.75 in) Harbison-Fischer seal-less single-acting pump. This pump is essentially a long, hardened stainless steel plunger running inside a corresponding hardened stainless steel barrel with only very small clearance. It was used to eliminate seal friction as a variable.

Instrumentation for these tests consisted of 16 channels of data. This array of instruments allows measurement of all relevant basic performance parameters to determine machine water-pumping characteristics as a function of wind speed.

A wind tracking sensor and a Max. 40 anemometer were located on a boom located 4.6 m (15 ft) above the rotor shaft (3 m [10 ft] above the rotor tip itself) and about 1.2 m (4 ft) behind it. This sensor gives a direct measurement of the angle of the wind with respect to the rotor axis, called the tracking error. Since it is 3 rotor radii away from the hub, errors in relative wind direction are likely to be small. This angle is important in evaluating the effectiveness of the tail in orienting the machine into the wind, which is very important at wind speeds near starting and below where furling becomes necessary. Since the power developed by the rotor drops off as the cube of the cosine of the tracking angle, tracking within a 10 deg. region results in power losses no more than 4.5%. If the tracking angle reaches 20 deg., losses increase to as much as 17%, which is unacceptable.

The Max. 40 anemometer located on this boom is 3 rotor radii (3R) above the RM Young reference instrument it and would be expected to have about a 4.6% higher wind speed just due to wind shear. In fact, the rotor deflects air to flow out around it, resulting in wind speeds 3R above the rotor that are more than 4.6% higher than the RM Young reference.

Since the O3C is down-wind from the Met tower for prevailing winds there is a delay of about 5 seconds when the wind is at 5 mph between speeds registered on the Met tower and on the windmill tower. Since our basic performance data is taken by sampling every second and recording averages over a one minute period, such delays will average out.

Other measurements included wind direction, machine yaw azimuth, RPM, air temperature, and barometric pressure.

Logging programs for the CR-10 included screen logging once per second, data logging to storage with measurements once per second with 1 minute averages recorded, and loads runs with data taken only from the load cell at 32 times per second. The latter data enabled plotting the indicator card for the pump and provided estimates of packing friction forces.

Test Setup

The well is drilled to 27.4 m (90 ft), and the top end of the pump is set at 19.2 m (63 ft). The quiescent water level is about 12.2 m (40) ft below the well head. Water is pumped up to a polished rod packing system and out a tee. Thence it passes by a surge tank of volume about 9.5 l (2.5 gal), depending upon its air pressurization. The surge tank smoothes the flow into the flow meter without causing significant delays. After passing through the flow meter, the water goes through a pressure regulator valve and into the line to the settling tank. While the O3C with its 9.5 cm (3.75") dia. and 30.5 cm (12 in) stroke pump can produce 76 l/min. (20 gal/min.), the well can only supply 38 l/min. (10 gal/min.). Thus for continuous operation the water must be returned to the well bore.

A strand of plastic tubing with open end is attached just above the pump body and runs to the surface. By applying pressure to this line from the surface, an equilibrium is reached in which the water pressure above the pump is measured by a pressure sensor and pressure gage at the surface. This is the system for measuring water depth and well draw-down. This line would not stay pressurized, possibly due to the air dissolving in the water, and a constant bleed to repressurize it is necessary. This system gives a reliable measure of the instantaneous water level in the well.

Simulating Greater Well Depth

The back-pressure system is capable of up to 100 psi back pressure on the outlet of the pump, which represents an extra force of about 500 kg (1100 lb.) on the pump. This load is sufficient to simulate pumping to a total pumping depth of 70 m (230 ft).

We do measure the average sucker rod loads, and can record instantaneous loads at up to 32 a times/sec for short periods. These loads represent the total load on the sucker rod, which include water weight, acceleration forces, pump friction, and polished-rod friction. From these loads, an approximation to the polished-rod friction can be made. Our polished rod system generated considerable friction. Because of this friction problem, the results taken with the lowest back pressure have the smallest estimated errors.

With the O3C capable of pumping twice as much as the well could supply, there was always an initial transient situation in which the well would try to pump off as soon as the machine was started. We had to partially furl the O3C to run at slow speed until the settling tank was siphoning properly to return the entire flow to the well bore.

Theory of Operation

The principal innovation of the Oasis wind pump is a patented adaptation of an oil-field-type engine and counterbalance system. This system utilizes a walking beam and horsehead, driven by Pitman arms attached to twin cranks at the ends of the crankshaft, shown schematically in Fig. 1. The system is a four-bar linkage, but the motions are close to sinusoidal. On the upstroke, the weights are falling and partially counterbalance the lift forces. On the downstroke, the residual loads on the sucker rod help to raise the weights for the next stroke.

Balancing

The starting speed can be minimized by reducing the starting torque. This can be done by providing enough counterbalance effect to make the crankshaft peak torque for lifting the water equal to the crankshaft peak torque for lifting the weights. The equations below assume that the motion is sinusoidal; nevertheless, these simple equations provide useful guidance and understanding.

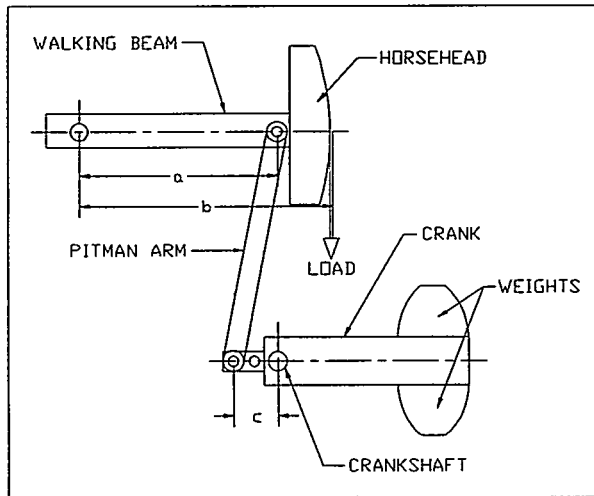


Figure 1 Counterbalance Mechanism

$$ECB = \frac{P_{up} + P_{down}}{2} \quad (1)$$

where ECB = effective counterbalance force at the horsehead

P_{up} = total load to be lifted by the horsehead on the up-stroke

P_{down} = total load to be lowered on the down-stroke

P_{down} represents all the weight hanging on the horsehead during the downstroke. This includes the weight of all components of the sucker rod string above the well head, the polished rod, plus the weight of all the sucker rod and pump below the well head as measured submerged in water.

P_{up} is equal to P_{down} plus the weight of water to be lifted. The water weight is calculated as the area of the pump cylinder times the depth down to the water surface times the weight per unit volume of water.

If there are any other forces that generate losses of energy, then the effects of these forces must be included in the analysis. A significant advantage of the Oasis design is that the lifting and counterbalance torques cancel each other out in the cranks, and the gears "see" only the greatly reduced resultant torque. This is apparent from considering Fig. 1. Reduced loads on the gear teeth imply lower wear and a correspondingly much longer life for both gears and bearings. This is the reason why this rotating counterbalance system has proven so effective and reliable in pumping the heavy loads for oil wells.

Packing & Pump Friction

Packing & pump friction have a direct effect on machine operation. On the upstroke, a constant friction force F does an amount of work = $F \times \text{stroke length}$. On the downstroke, the load P_{down} helps accelerate the

rotor, so a friction force also extracts energy. Substitute P_{up} with $P_{up}+F$ and P_{down} with $P_{down}-F$. In equation (1) the friction force cancels out, so has no effect on the balancing.

On the other hand, when the machine is perfectly balanced according to equation (1), the peak crankshaft torque is, approximately

$$Q_{peak} = (b/a)c(P_{up} - P_{down})/2 \quad (2)$$

where c is the offset between the crank and the lower Pitman bearing centers.

Again, let us check the effect of a sucker rod friction load, so substitute P_{up} with $P_{up}+F$ and P_{down} with $P_{down}-F$. In this case the friction does not cancel out, so that

$$Q_{peak} = (b/a)c(P_{up} - P_{down} + 2F)/2 \quad (3)$$

Thus a friction force directly increases the peak torque by the amount

$$Q_{peak} = (b/a)c(2F) \quad (4)$$

With this torque increase comes a direct increase in starting speed, since the rotor must generate an extra torque of this amount divided by the gear ratio.

Peak Torque Ratio

Since starting wind speeds depend on the peak torque, it is of interest to find the ratio of the peak crankshaft torque without counterbalancing to that with counterbalancing. This is useful in comparing a the O3C with standard farm windmills, which are not counterbalanced. Using the above equations, we find the peak torque ratio to be:

$$PTR = \frac{2}{1 - \frac{P_{dn}}{P_{up}}} \quad (5)$$

For the idealized case when the sucker rods & pump are weightless, $P_{dn} = 0$ and the torque is reduced by a factor of two, implying a reduction in starting speed of $\sqrt{2}$. If P_{dn} is half of P_{up} , that is, the sucker rod dead weight and water weight are equal, the PTR is 4. In this case the peak torque is reduced by a factor of 4, implying a reduction in starting speed of a factor of two. In the extreme case when $P_{dn} = P_{up}$ the PTR increases without bound. This situation would be approached if the static lifting load were a large fraction of the total lifting load.

Results

The first set of data shown was taken at a 30.5 cm (12 in) stroke pumping at 12.2 m (40 ft). and is shown in Fig. 2. The system efficiency shown is calculated based upon the Betz limit, not charging the machine with performance which is impossible to attain. Thus the system efficiency is the actual hydraulic power divided by the power realized by an ideal rotor. It is seen that the maximum system efficiency occurs at 7.5 mph and a tip speed ratio (TSR) of about 1.25. The maximum efficiency is 40%, which can be compared with the maximum efficiency of a conventional 2.44 m dia. wind water pumper measured at U.S.D.A. Bushlandⁱⁱⁱ, TX of 27%. Thus this represents a 50% higher efficiency, although the machine size and depth of pumping were different.

With the 3:1 gear ratio, a wheel RPM of 100 represents the allowed maximum stroke rate, reached at about 20 mph. Please note that the use of a heavy pump (98 lb.) and steel 5/8" sucker rod with other sucker rod tares resulted in a downstroke load of about 247 lb. on the O3C. On the upstroke about 191 lb. of water weight would be added. This is a much greater load than would be felt by an ordinary well installation at this depth and stroke. Consequently it is not representative of normal pumping at this condition. To properly account for all these variables and extend the results, we needed a math model.

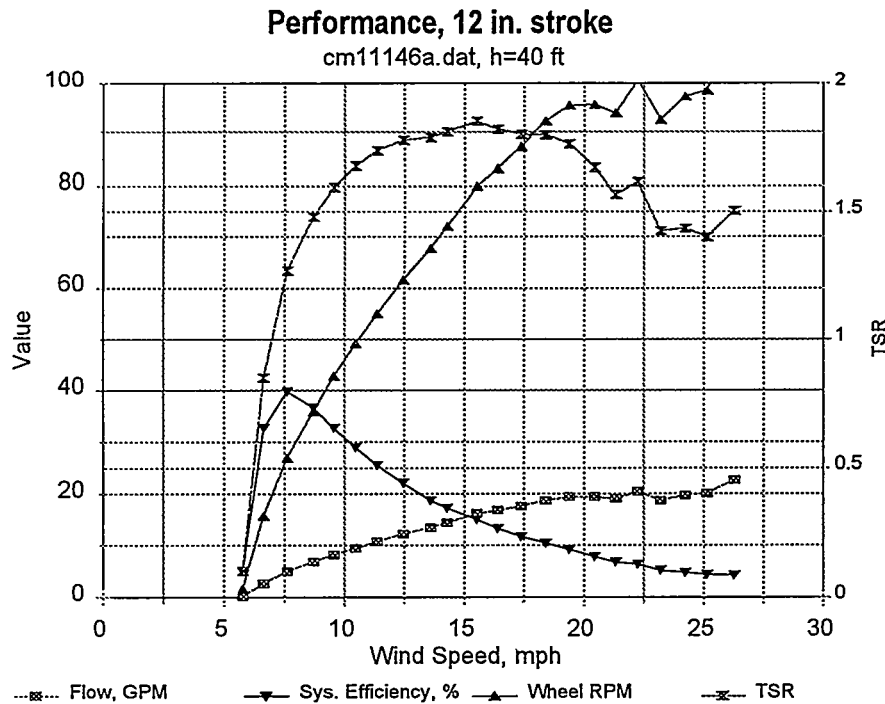


Figure 2 Performance, 12" stroke @ 40 ft

at higher TSR's. By doing an analysis of forces on the lower Pitman bearing to find Effective Counter Balance (ECB)

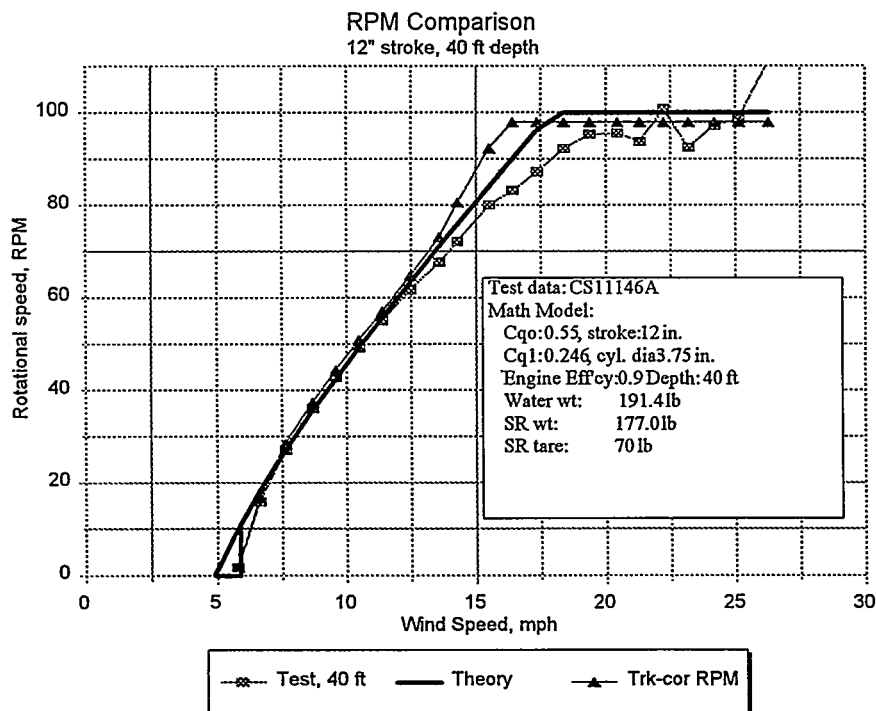


Figure 3. Theory vs. test, 12" stroke, 40 ft

Math Model Development

In developing the math model, it was found that momentum theory models such as PROP would not predict the starting torque or low-speed running torque of the rotor. This point was determined from experimental data based on starting wind speed with known sucker rod loads, following work of J.A.C. Kentfield^{iv}. A linear C_p vs. TSR model was used to predict the power absorbed by the rotor

forces for a given position of the counterweights, assuming a net gearbox efficiency of 90%, and allowing for losses caused by polished-rod friction based on forces as measured by the load cell on the sucker rod, a model was developed. Using the parameters of three of the test conditions, the model was used to predict the test results. The comparison of model and test data is shown in Figures 3, 4, and 5.

The effect of starting friction is shown as a vertical

line. Once started, the machine will continue to operate down to lower wind speeds until the rotor torque is not sufficient to overcome the peak torques. The machine tracked well but not perfectly, and the curve shown as Trk-cor is corrected for tracking error, i.e., shows the RPM to be expected if the tracking were perfect. This was basically a high-wind data set with no data below 5.17 mph, so the form of the experimental curve is not well-defined below about 7 mph in this set.

The math model predicts the performance very well, except at very high RPMs when the furling response of the tail serves to pull the rotor out of the wind. The effect of furling has not been incorporated into the math model as yet.

The second set of test data was taken for a 30.5 cm (12 in) stroke and a simulated extra 15.2 m (50 ft) of pumping depth, as shown in Fig. 4. The effect of polished-rod packing friction was accounted for in the results. This was basically a low-wind data set, and the experimental definition of performance near and below the starting speed should be good. Again, the math model does a very good job of representing the machine performance. The predicted starting speed without counterbalancing, with the heavier load and

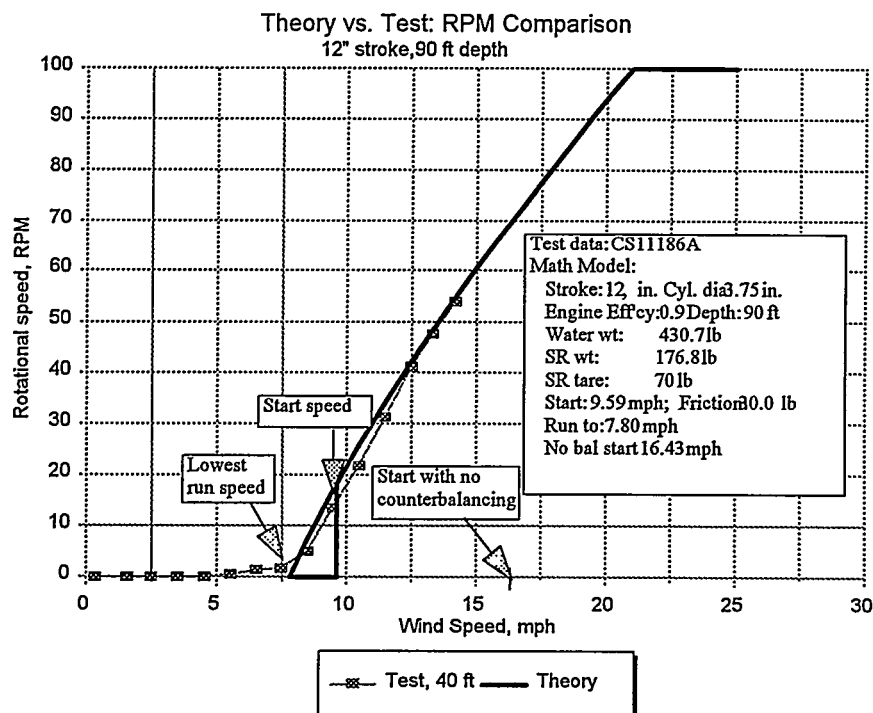


Figure 4 Test vs. Theory, 12" stroke, 90 ft

friction, is indeed high at about 7.3 m/s (16.43 mph).

The third data set was taken with the O3C set on the short stroke and is shown in Fig. 5. To reduce the counterbalance effect, all weights were removed from the cranks. Later analysis showed that the machine was considerably out of balance, the cranks themselves being too heavy. The effect of being out of balance was to increase the starting speed, and that effect is indeed shown in the results. Another effect of the short stroke is that linear speeds are much smaller and stiction may have a correspondingly greater effect during starting. The predicted starting speed for a comparable un-counterbalanced machine is 2.29 times as high as that of the O3C.

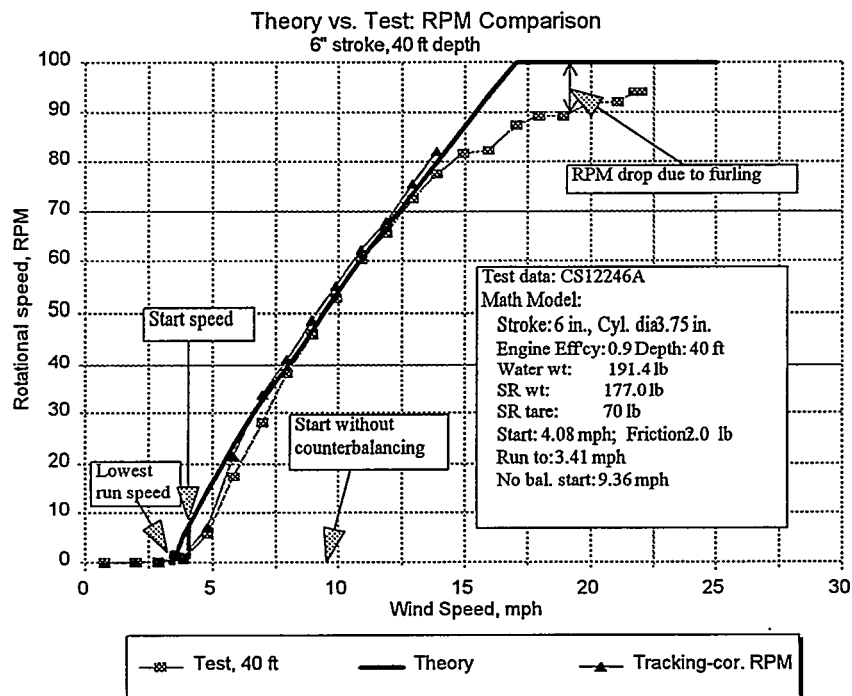


Figure 5 Theory vs. Test, 6" stroke, 40 ft

That the model represents the O3C performance so well gives us confidence that we can predict the performance for any other condition with good accuracy.

As a final note on the experimental work, revisiting the multibladed farm windmill shows the significance of accurate tower-well alignment, the pronounced effect of pump and polished-rod seal friction losses on machine performance, and the limitations due to the dynamics of sucker rods, pump, and valves at high stroke rates.

Effect of Counterbalance on Starting Torque

The effect of counterbalancing on crankshaft torque is shown in the math model predictions of Fig. 6. That the predicted torques are not exactly sinusoidal is apparent from examining these curves.

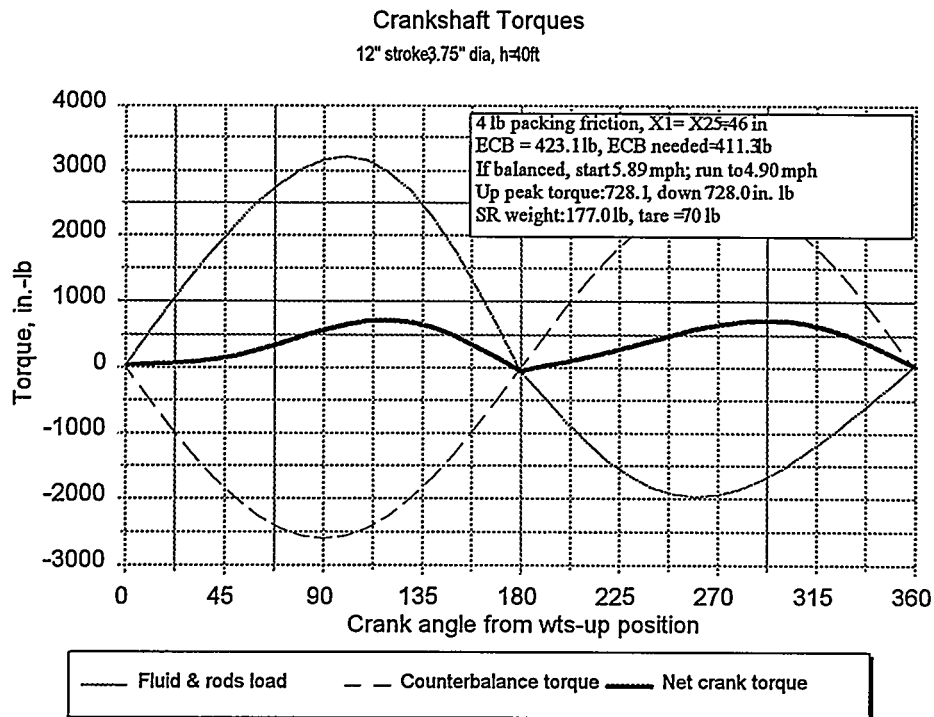


Figure 6 Effect of Counterbalancing

torques are major benefits of the Oasis design.

Looking again at the predicted and measured performance in Fig. 3, the O3C would be producing 60% of its maximum output before a conventional machine would even start. Corresponding reductions in starting wind speed are apparent in the comparisons of test data and theory in Figures 4 and 5.

Design Advantages

From several years of testing and math modeling, the major advantages of the Oasis design are as follows:

- Excellent low-wind starting capability, will start in winds 30 to more than 50 % lower than conventional units.
- Can be set up heavily loaded without resulting in very high starting wind speeds.
- Can pump very large flow rates at low pumping heads and still have low starting wind speeds.
- Can pump to greater depths than un-counterbalanced machines and still have low starting wind speeds.
- The forces on gears and bearings are greatly reduced (to 1/2 or 1/4 or better) over those on un-counterbalanced machines, resulting in lower wear and much longer life.
- Very effective wind tracking in low winds.
- Retains very high volumetric efficiency at starting speeds and above, since resorting to use of a leakhole to reduce a high starting wind speed is unnecessary.

The torque reduction caused by balancing is clear. Numerically, the reduction is from 3212 in.-lb. down to about 728 in.-lb. This is a reduction of 4.41, and yields a reduction in starting speed of a factor of 2.1 according to Equation 5.

Again we note that the gears and bearings "see" only the 730 in.-lb. peak torque.

The reduced starting speed and reduced load

Conclusions

The Oasis 3C has been tested and a math model developed that predicts its performance for three test conditions, and presumably for other conditions as well. The results are found to agree with simplified equations that assume a sinusoidal load torque, yielding insight into the effectiveness of the oil-field rotary counterbalancing approach. The anticipated torque reductions of the Oasis design have been shown to agree with the measured results in RPM comparisons.

Use of the math model allows tailoring of the installation of an Oasis 3 for a particular well and wind conditions. This should be a significant improvement over previous methods.

The advantages of the Oasis counterbalanced design are found to be related to the torque reduction on the gears and the fact that the machine is capable of starting in low winds even if it is set up with a pump diameter and pumping depth that load the machine more than a conventional windmill.

With the development of the elevated tail, the O3C has been shown to track the wind direction with acceptably small errors at the low wind speeds in which it is capable of starting.

Future Work

Testing of the Oasis 3C has proven the advantages of the Oasis design. A number of modifications and improvements have since been incorporated. The revised machine, denoted the Oasis 3D, will be subject to a beta test program. Five units are being produced and will be operated by prospective owners at various sites for a 6 month period to test the improvements that have been made. A production development phase should then lead to series production. Additional testing involving long-term water pumping measurements and math modeling of the furling system is planned. This should permit good estimates of water production based on wind speed distributions for a given site.

ⁱ Fraenkel, Peter, *Water Pumping Devices, A Handbook for Users and Choosers*, U.N. Food and Agriculture Organization, 1986, Reprinted by Intermediate Technology Publications, London, 1990, Fig. 120 & p. 107.

ⁱⁱ Lysen, E.H., *Introduction to wind energy: Basic and advanced introduction to wind energy with emphasis on water pumping windmills*, CWD report, May, 1983.

ⁱⁱⁱ Molla, S. & Nolan Clark, *Analysis of two mechanical wind pumping systems*. AWEA WindPower, '94 Proceedings, p. 261-268.

Clark, R. Nolan, *Comparison of two mechanical windmills for pumping water*, AWEA WindPower '95 Proceedings, p. 457-463.

^{iv} Kentfield, J.A.C., *A performance comparison of various wind-turbine types for powering water pumps*, 17th Intersociety Energy Conversion Engineering Conference, Los Angeles, Aug. 1982.

AN INTRODUCTION TO THE SMALL WIND TURBINE PROJECT

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ABSTRACT

Small wind turbines are typically used for the remote or rural areas of the world including: a village in Chile; a cabin dweller in the U.S.; a farmer who wants to water his crop; or a utility company that wants to use distributed generation to help defer building new transmission lines and distribution facilities. Small wind turbines can be used for powering communities, businesses, homes, and miscellaneous equipment to support unattended operation. This paper covers the U.S. Department of Energy/National Renewable Energy Laboratory Small Wind Turbine project, its objectives, the subcontractors and their small wind turbine concepts.

SMALL WIND TURBINE MARKET

Small wind turbines are used throughout the world and are primarily used in rural or remote settings in the domestic and international markets. Small wind turbines can be used to power communities, businesses, schools, clinics, and miscellaneous equipment. Small wind turbines can be developed to meet the needs of a variety of equipment. Small wind turbines are suitable for the domestic and international (developed and developing) markets.

Domestic Markets

In the United States, 24% of the population lives in rural areas and a growing number live remotely. Most of those individuals have access to the grid, but there is a group of customers where the cost to connect with the utility grid is prohibitive. For those off-grid individuals, diesel generation systems, renewables (solar, wind), and a storage device (batteries) used in combination as a hybrid power system could provide a solution.

International Markets

Currently, 50% of the international rural sector (not necessarily agricultural) population does not have electric power.¹ An estimated 2 billion people do not have access to electricity. This figure is projected to increase to 3 billion by the year 2030. Within the international market, there are two market groups: the developed countries and the developing countries. In the Organisation for Economic Cooperation and Development (OECD) nations or developed countries, electric needs are met with a mature market, with developed infrastructure and a stable population. OECD nations will experience slow growth in the power market, estimated to be at 0.7%/year.² OECD countries have typical needs for grid-connected technology, which makes this market similar to the domestic market.

In developing countries, energy needs are driven by migration to urban areas, growth in per capita income, increased use and manufacture of energy intensive products, and poor efficiency in providing power. Worldwide growth in energy services is expected to be seven times that of the OECD countries (5.3%/year).³ The World Bank has estimated that within 15 years, the total energy consumption will be greater in the developing world than in the OECD countries. "At present, in some developing countries, between one-third and one-quarter of available public resources are going into the electric power sector, and these investments are still inadequate. The aggregate investment demand for electricity in the developing countries is U.S. \$100

billion over the next decade.”⁴

SMALL WIND TURBINE PROJECT

The Department of Energy added the Small Wind Turbine project to the Turbine Research program in 1995 to stimulate the application of advanced technology in that portion of industry that serves specialized markets requiring wind turbines in sizes from 5 to 40 kW. Such systems are deployed in a wide range of commercial applications, often high value end-use applications in remote sites that require high reliability over extended periods of unattended operation.

The goal of the Small Wind Turbine project is to help U.S. industry develop cost-effective, high reliability small wind turbine systems for both the domestic and international wind energy markets. The objective of this project is to provide tested small wind turbine systems, sized from 5 to 40 kW (maximum power), that meet a Cost/Performance Ratio of \$0.60/kWh or less at 5.4 m/s (12.1 mph) sites and significantly reduce the cost of energy by the year 2000. The systems are also expected to meet certain design requirements such as: high reliability, ease of transportation and installation, low maintenance, International Electrotechnical Commission (IEC) Class II requirements, and environmental considerations (desert, coastal, cold weather) based on specific markets.

The scope of work emphasizes an iterative engineering development process, including formal design reviews at the end of each project stage and tests to verify the system design and analyses (see Figure 1).

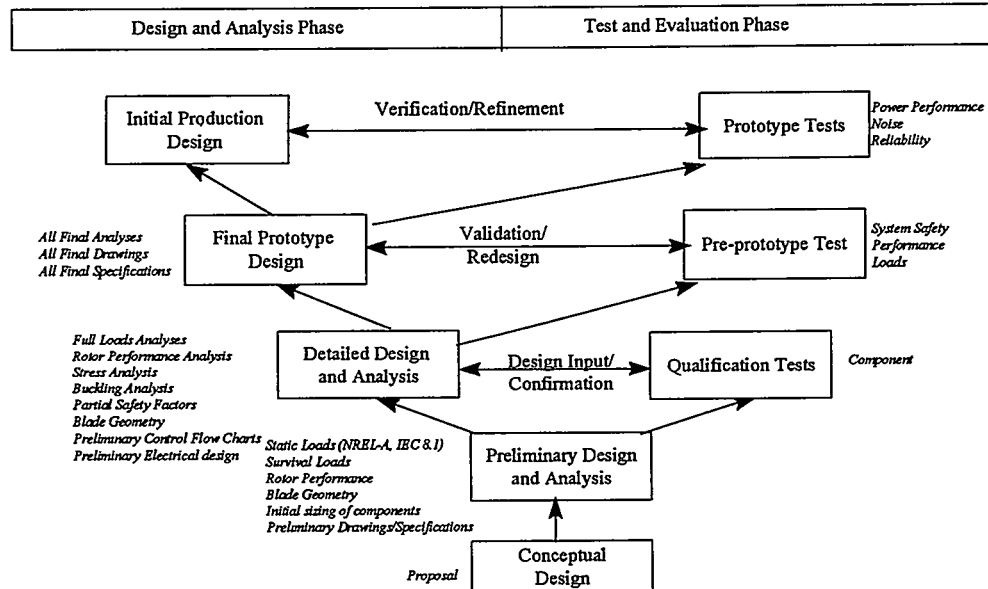


FIGURE 1 - SMALL WIND TURBINE ENGINEERING DEVELOPMENT PROCESS

The first stage will develop a preliminary design for the prototype turbine based on the subcontractor's market assessment and proposed concept. Stage two will generate detailed designs of components and

subsystems, which will be verified through qualification tests. Information obtained in the design process and qualification tests will be integrated into a pre-prototype turbine design. Stage three will fabricate and test the pre-prototype turbine at a site chosen by the subcontractor to validate the operational, safety, and structural characteristics of the system design. Pre-prototype test results will be used to refine the system design, as necessary, to complete a final design for the prototype turbine. Stage four will upgrade the pre-prototype test turbine to the final prototype configuration. The prototype turbine, which is the definitive product resulting from the Small Wind Turbine project, will be field tested for 1,000 run-time hours at the National Wind Technology Center (NWTC) to evaluate system performance and reliability. During this 1,000 hour run-time test, the turbines will be tested to meet certain IEC testing requirements including: power performance (IEC 1400-12), and acoustics (IEC 1400-11), as well as reliability inspections and loads measurements. After installing the prototype turbine at the NWTC, the subcontractor will document the final design and analyses in preparation for certification and production. Final drawings, engineering specifications used to procure and inspect components, and bills of materials will be developed in order to completely document the resulting engineered product. The anticipated period of performance for these subcontracts is 36 months.

SPECIFICATIONS

Specifications listed in the Request for Proposal (RFP) include: 5-40 kW maximum power; high reliability; low maintenance; ease of installation and transportation; identification of extreme environmental considerations (coastal, desert, cold weather); a cost performance ratio – turbine system cost/net annual energy production (AEP_{net}) of \$0.60/kWh (5.4 m/s); use IEC class II guidelines (resource of 8.5 m/s, wind gust for 100 year of 132 mph) for analysis and design; and a COE that will be reduced by year 2000. Specific explanation of the market drivers for each specification (shown in *italics*) are provided below.

5-40 kW Size

Review of available small wind turbines data identified approximately 25 manufacturers (3 U.S. manufacturers) throughout the world that produce small electricity-generating wind turbines in the 5-40 kW rated power range as of 1996. In addition, approximately 10 wind turbines over 6 m in rotor diameter are being manufactured internationally for water pumping. Based on market potential, small number of U.S. manufacturers, and the desire to advance the technology, NREL targeted the 5-40 kW range for development.

High Reliability and Low Maintenance

This requirement of high reliability and low maintenance is driven primarily by the need to have operating wind turbine systems in remote or developing locations throughout the world. Unlike utility grade turbines, small wind turbines are typically sold in small groups or as stand-alone installations. This adds to the maintenance costs since turbines are not co-located. Maintenance could involve a trained windsmith who would have to travel potentially significant distance to maintain a few or one wind turbine system. An alternative is to get in-country support and have detailed simple instructions for scheduled maintenance and easy unscheduled maintenance. The sensitivity to high reliability and low maintenance increases as the remoteness of the location increases.

Ease of Transportation and Installation

Ease of transportation is necessary for international markets that require the use of standard shipping containers for transporting the small wind turbine systems. The primary market drivers for ease of installation are the developing countries that do not have the infrastructure (roadways, lifting equipment, and transportation systems) to support small wind turbine installation and erection. Domestic customers living in rural or remote areas may also have limited access to lifting equipment necessary for turbine erection.

Cost Performance Ratio

The Cost Performance Ratio (CPR) is an annualized figure of merit that is defined as the turbine system cost (cost of the turbine system and tower without installation) divided by the net annual energy production. It does not account for life-cycle costs, balance of station costs, or operations and maintenance costs. CPR encourages the designer to lower turbine system cost and increase annual energy production, consistent with the procurement goals and objectives.

NREL selected CPR as the primary figure of merit for the Small Wind Turbine project to compare the proposed turbine concepts and to track the development of the design throughout the project. Figure 2 shows average cost performance data for small wind turbines in the 5-40 kW size. CPR data compiled from individual turbine manufacturers ranged from 0.48 to 2.43 (\$/kWh). When the data was normalized based on the rated power, as shown, CPR does not fall below the \$0.60/kWh or less target (at 5.4 m/s sites) set for the Small Wind Turbine project.

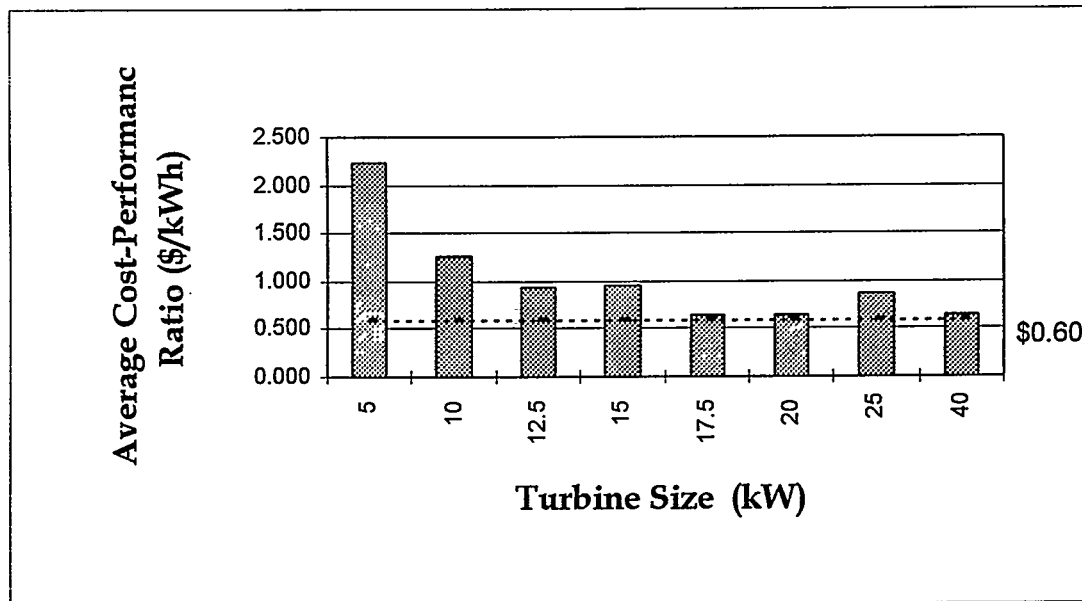


FIGURE 2 - AVERAGE COST PERFORMANCE RATIO VERSUS TURBINE SIZE (5-40 kW)

Reduced COE

The Small Wind Turbine project also requires the subcontractor to significantly reduce the cost of energy (COE) of the proposed concept, relative to the COE of its baseline turbine, by the year 2000. The life-cycle COE accounts for initial capital costs (turbine system and balance of station costs), annual operations and maintenance costs, levelized replacement costs, and net annual energy production, including losses due to blade soiling, the collection system from turbines to the grid, and miscellaneous losses.

For small wind turbines, COE varies widely depending on the application, location, and other factors, such as financing costs. Reliable cost information necessary for calculating COE is not readily available. As a result, NREL did not select COE as the primary figure of merit for this project. While the basic units of the CPR are similar to COE, the two figures are not directly comparable because COE is a life-cycle cost model and CPR is annualized.

IEC Class II Design Load Cases

Recent sales in OECD or developed countries have required certification of wind turbines. To ensure that the small wind turbine designs will be ready for certification at the end of this project, NREL has based its design requirements on IEC standards. The turbine designs must meet IEC wind turbine Class II parameters, as a minimum requirement. Class II references an extreme wind speed of 42.5 m/s or 132 mph and a minimum of a 20 year service life. The subcontractors will be required to use design load cases identified in IEC 1400-1 "Wind Turbine Generator Systems - Part 1: Safety Requirements."

APPLICATIONS

Because of the diversity of potential end-uses, proposers were asked to specify their target market and application for their turbine concept in order to fold in any requirements early in the design phase. Applications were categorized as grid-connect or constant AC load, wind electrification or variable AC load, or battery charging or DC load (see Figure 3). Combinations of applications or other applications were considered in the proposal evaluation as long as the primary output of the turbine was electricity. Grid

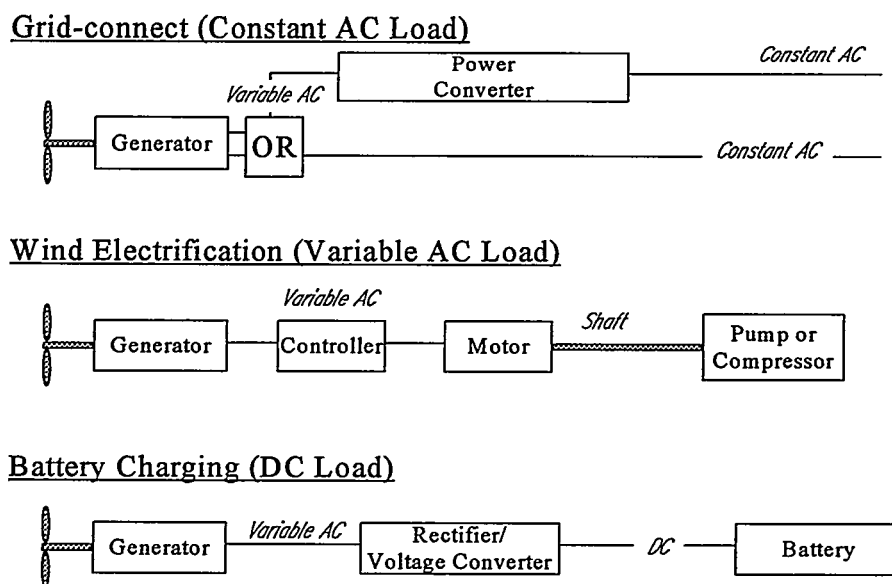


FIGURE 3 - SMALL WIND TURBINE APPLICATIONS

connect can include three-phase or single-phase electricity, and the systems could be owned by utilities, rural electrification associations, or community mini-grids (either hybrid or battery charging stations). Hybrid systems are defined as multiple power sources (e.g., wind turbines, photovoltaics, diesel generators, fuel cells) linked together to serve stand-alone or small grid electric power needs. Hybrid systems may include power electronics (e.g., rectifier, inverter), batteries or other forms of storage and dump loads. Wind electrification is power used directly to run compressors, or shafts (e.g., water pumping, ice making, stripper wells). Intermittent generation is often acceptable for wind electrification applications, so batteries or other storage are minimal if required. Battery charging is the third application sought in the RFP. Battery charging systems are used in remote applications that require continuous power, such as telecommunication stations and community battery charging stations. Dump loads are often included in battery charging systems to

handle the excess power after the battery is fully charged.

The RFP was written with the above specifications and applications in mind. However, proposers could modify their specifications or applications based on their understanding of the market. The RFP was released on June 5, 1996. Responses to this request were received by September 5, 1996, and subsequent selections were made to four companies: Bergey Windpower Company; Cannon/Wind Eagle Corporation; WindLite Company; and World Power Technology, Inc. Negotiations are in process with each of the companies with subcontract awards expected in the July through October time frame.

SUMMARY OF SUBCONTRACTORS AND PROPOSED CONCEPTS

Figure 4 shows an artist's rendition of proposed concepts for each subcontractor in the Small Wind Turbine project. Three of the proposed concepts are based on a typical small wind turbine configuration (upwind, variable speed, furling overspeed control) and one concept is based on a configuration used on some larger, utility-scale machines (downwind, constant speed, overspeed control such as aerodynamic brakes or pitch).

Bergey Windpower Company (BWC) is a family-owned manufacturing and project development company formed in 1977 in Norman, Oklahoma. Their company produces three small wind turbines rated at 0.85, 1.5, and 10 kW (BWC 850, BWC 1500 and BWC EXCEL) and has sold 1,600 turbines worldwide since production began in 1980. BWC has sold its products in more than 70 countries and is well known for pioneering work in village power and pumping. Mike Bergey will be the project manager and his team will be supported by Karl Bergey, Dr. Kenneth Craig, Pieter Huebner, and Dr. Michael Selig (University of Illinois).

The proposed 40-kW concept is a three-bladed, upwind, variable-speed, furling machine that meets the market requirements for village power, primarily battery charging. The proposed rotor diameter is 14-meter with a 55-m tower, and different rotor diameters will be available to optimize performance for different wind regimes. The pre-prototype turbine will be tested in Norman, Oklahoma, followed by prototype turbine tests at the NWTC configured as a battery charger.

Cannon/Wind Energy Systems has been in the business of operating and maintaining windfarms in Tehachapi, California since 1982. During that time, Cannon has installed over 1,100 turbines and currently manages and operates 567 wind turbines manufactured by Nordtank, Micon, Vestas, and Cannon. The Cannon/Wind Eagle WE-14 team consists of Craig Loke, Fred Beasom, Jeff Wilks, Robert Ochoa and consultants including Jamie Chapman, Ruth Heffernan-Marsh, Jay Carter, Sr., Kevin Jackson, and Woody Stoddard.

The proposed 25/30-kW concept is the culmination of more than 15 years of research, design, and development of a lightweight, flexible turbine design. It is based on a scaled-down model of the 300-kW Wind Eagle utility-grade turbine which is currently under development. The concept is a two-bladed, large load-shedding 14-meter diameter rotor, downwind, constant speed, gimballed nacelle turbine with a 36.6 m tilt-down tower.

WindLite Corporation is a new corporation, but is made up of senior people with experience in the wind energy field. Robert Lynette will act as the president and marketing director, with Jay Jayadev as the project manager and Jim Sencenbaugh as the principal investigator. The WindLite team will draw on technical resources from R. Lynette and Associates. It will also be supported by Mick Sagrillo of Lake Michigan Wind and Sun and a team of consultants.

Small Wind Turbine Project

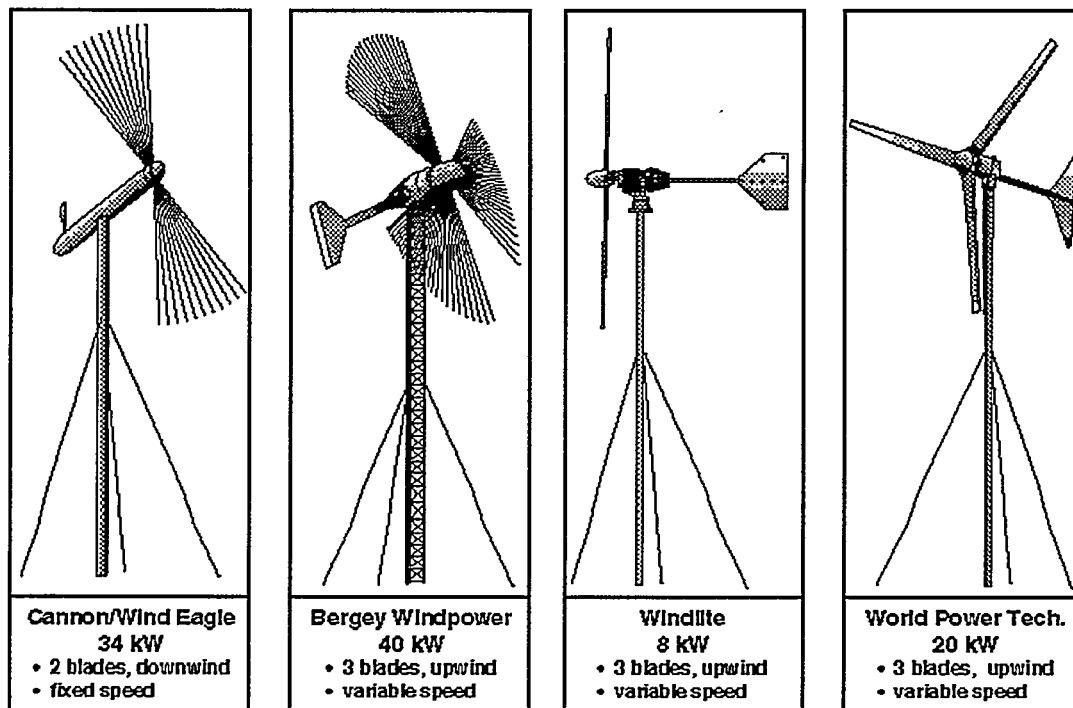


FIGURE 4 - SMALL WIND TURBINE PROPOSED CONCEPTS

The proposed 8-kW concept is a three-bladed, 6.7-meter diameter rotor, upwind, variable speed, furling turbine. The primary application for this wind turbine is battery charging. WindLite will perform their pre-prototype tests at Altamont Pass, close to its facility in Mountain View, California. A prototype will be tested the NWTC as a battery charger.

World Power Technology has been in business since 1974, starting with its Whisper 1000 machine which was followed by the Whisper 600, Mariner H500, Whisper 3000, Whisper 4500, and Whisper 900. World Power Technology produced its thousandth Whisper 1000 in November 1996 and has produced 2500 machines in total. World Power is located in Duluth, Minnesota, and is overseen by a board of directors that have experience in developing products for various domestic and international markets. Elliott Bayly will be the principal investigator, and Robert Clarke (President of Alpen) will be the project manager.

The 20-kW proposed concept is a three-bladed, 9-meter rotor diameter, upwind, variable-speed, furling turbine targeted for grid-connect applications. The pre-prototype will be tested at a site in Minnesota owned by World Power Technology. The pre-prototype will then be upgraded to the prototype configuration and tested at the NWTC as a grid-connect turbine.

CONCLUSION

The DOE/NREL Small Wind Turbine project will enable the U.S. wind industry, national laboratories, and

consultants to pool their knowledge and develop cost-effective, high reliability small wind turbines for domestic and international wind energy markets. Four companies were selected through a competitive procurement to develop advanced small wind turbine systems for deployment in a wide range of commercial applications. The turbine designers will follow an iterative engineering development process that will include formal design reviews at the end of each project stage and tests to verify the system design and analyses. Documentation necessary for IEC Class II turbine certification will be completed by the end of the project.

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NEW AIRFOILS FOR SMALL HORIZONTAL AXIS WIND TURBINES

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ABSTRACT

In a continuing effort to enhance the performance of small energy systems, one root airfoil and three primary airfoils were specifically designed for small horizontal axis wind turbines. These airfoils are intended primarily for 1–10 kW variable-speed wind turbines for both conventional (tapered/twisted) or pultruded blades. The four airfoils were wind-tunnel tested at Reynolds numbers between 100,000 and 500,000. Tests with simulated leading-edge roughness were also conducted. The results indicate that small variable-speed wind turbines should benefit from the use of the new airfoils which provide enhanced lift-to-drag ratio performance as compared with previously existing airfoils.

I. INTRODUCTION

Over the last 12 years, a considerable number of airfoils have been specifically developed for horizontal axis wind turbines (HAWTs).^{1–7} For example, 25 specially tailored airfoils for wind turbines originated from the joint work between the National Renewable Energy Laboratory (NREL) and Airfoils, Inc.¹ For wind-turbine applications, the advanced NREL airfoils have been shown to provide aerodynamic and structural advantages as compared with those associated with the myriad of airfoils originally designed for airplane applications. There are, however, only a limited number of wind-turbine airfoils that have been developed exclusively for small blades.

Typically, the entire span of the blades of small HAWTs operate at low Reynolds numbers where laminar separation effects can severely degrade the performance of airfoils not designed for this flow regime. In addition, the typically fast rotational speeds of small HAWTs provide centrifugal stiffening that reduces the blade bending loads and thus, allows for the use of thinner airfoils as compared with those designed for larger wind turbines. Reductions in laminar separation effects and in airfoil thickness provide an increase in aerodynamic performance, which yields better energy capture. Therefore, owing to low Reynolds number aerodynamics and centrifugal stiffening effects, wind-turbine airfoils designed for medium and large blades are not particularly suitable for smaller blades.

A number of existing low Reynolds airfoils, which were designed for small unmanned aerial vehicles, have been shown to be applicable to small wind turbines.⁸ Specially tailored airfoils for small HAWTs, however, should provide enhanced performance. From the

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literature, it appears that the S822 and S823 airfoils are the only two airfoils that have been specially designed for small blades.¹ These two airfoils are principally intended for stall-regulated HAWTs and form one of the nine advanced NREL airfoil families.¹ Consequently, there is a need for new wind-turbine airfoils for small HAWTs, especially for those operating in variable-speed mode.

In a continuing effort to support new blade designs for small HAWTs and improve their performance, a total of four airfoils were designed and wind-tunnel tested. These airfoils are intended primarily for 1–10 kW rated power variable-speed wind turbines for conventional (tapered/twisted) or pultruded blades. Section II describes the airfoil design objectives and methodology. A brief description of the wind-tunnel facility, measurement techniques, and data reduction method is provided in Section III. Section VI provides a discussion of the wind-tunnel test results, including tests with fixed transition to simulate leading-edge roughness caused by blade erosion, accumulation of insect debris, etc. Finally, conclusions are given in Section V.

II. AIRFOIL DESIGN OBJECTIVES AND METHODOLOGY

In this design work, the focus has been on designing airfoils that can be used along the entire blade span of small variable-speed HAWTs. Three airfoils, referred to as the primary airfoils, were designed to provide optimum performance over a broad range of operating conditions. Considering the low operating Reynolds numbers and beneficial centrifugal stiffening effects of small HAWTs, the airfoil thickness for the primary airfoils was fixed at 10%. A 16% root airfoil was also designed to accommodate possible large root bending moment and large blade-stiffness requirements. With the root airfoil over the inboard 30% of the blade, the primary airfoils are recommended for use over the last 25% of the blade (from the 75% station to the tip), with blending between 30% and 75% of the blade span. The root airfoil (SG6040) and the three primary airfoils (SG6041, SG6042 and SG6043) are depicted in Fig. 1.

During normal operation, variable-speed HAWTs operate below stall and over a relatively limited lift range as compared with constant-speed wind turbines. For these operating conditions, minimizing leading-edge roughness effects, such as no loss in the maximum lift coefficient, is not particularly critical.^{1,9} For optimum aerodynamic performance during variable-speed operation, the low-drag lift range (drag bucket) can be reduced in favor of greater lift-to-drag ratios. Accordingly, the primary airfoils were designed to achieve as high a lift-to-drag ratio as possible at the design lift coefficient, ranging from 0.6 to 1.2. The primary airfoil having the lowest design lift coefficient was expected to yield large blade chords and consequently, the root airfoil was designed to be mainly used with the two other primary airfoils. To account for possible variations in the tip speed ratio (TSR) caused by atmospheric turbulence, the best lift-to-drag conditions were designed to occur over a range of lift coefficients centered about the design lift coefficient.

The design Reynolds numbers for the four airfoils were selected according to the tradeoff between operating lift coefficient C_l and Reynolds number Re . It has been shown that for an optimum variable-speed rotor, the product of the lift coefficient and Reynolds number is nearly constant for a particular blade station,¹⁰ i.e.,

Table 1 Airfoil design objectives.

Airfoil	t/c	Design C_l	Design Re
SG6040	16%	1.1	200,000
SG6041	10%	0.6	500,000
SG6042	10%	0.9	333,333
SG6043	10%	1.2	250,000

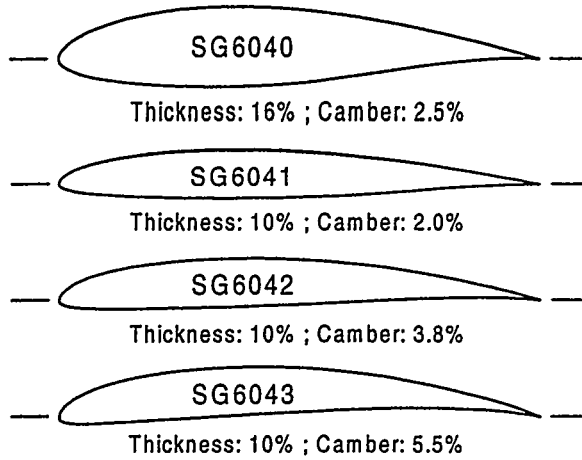


Fig. 1 Contours of the root and primary airfoils.

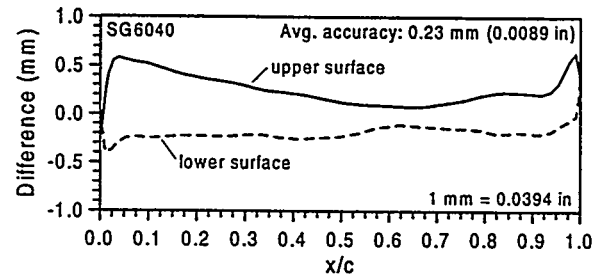


Fig. 2 Contour accuracy plot for the SG6040 airfoil.

$$\mathcal{R} = Re C_l \quad (1)$$

Here, $\mathcal{R}$ is the reduced Reynolds number which is constant so long as the TSR , the local velocity and axial induction factor of a given blade station remain constant. Therefore, the potential increase in the maximum lift-to-drag ratio from operating at a high lift coefficient is reduced by a lower operating Reynolds number according to Eq. (1) and vice versa. The design Reynolds number for each primary airfoil was determined using Eq. (1) and a reduced Reynolds number $\mathcal{R}$ of 300,000. For the root airfoil, a design Reynolds number of 200,000 was used. The objectives for the four airfoils are shown in Table 1.

To achieve the design objectives, the new airfoils were systematically designed using PROFOIL,¹¹ which is an inverse airfoil design method. In addition, the Eppler code¹² and XFOIL¹³ were used to obtain preliminary airfoil performance characteristics to guide the design. With PROFOIL, the desired velocity distribution is prescribed, from which the corresponding airfoil shape is determined. In tailoring the velocity distribution for each airfoil, a gradual transition ramp was introduced on the upper surface to minimize laminar separation effects such as bubble drag. The need for a shallow pressure gradient combined with a high-lift requirement lead to aft-loading and, consequently, a relative high pitching moment coefficient ($-0.08 < C_{m,c/4} < -0.14$). Note that the reduction in the size of the drag bucket caused by the use of aft-loading is not a drawback for variable-speed HAWTs because, as mentioned previously, they operate over a relatively limited lift range. The primary airfoils have similar velocity distributions that differ mainly by their respective amount of aft-loading. Therefore, the aerodynamic characteristics of the three primary airfoils are related and these airfoils can be considered as an airfoil series. The addition of the root airfoil to the primary airfoils provides a unique airfoil family for variable-speed HAWTs.

III. TESTING APPARATUS AND METHODS

The experiments were performed in the University of Illinois at Urbana-Champaign low-turbulence subsonic wind tunnel having a 0.857 m (2.81 ft) high and 1.219 m (4 ft) wide test section. For the airfoil tests, two 1.829 m (6 ft) long Plexiglas splitter plates were inserted into the test section and reduced the test section width to 0.854 m (2.802 ft). With an empty test section, the turbulence intensity of the tunnel is less than 0.1%¹⁴ for the test Reynolds numbers. The 0.305 m (1 ft) chord airfoil models were made of foam with a fiberglass finish and were inserted horizontally between the splitter plates with nominal gaps of 1–2 mm (0.040–0.080 in). Using a coordinate measuring machine, each airfoil model was digitized at mid-span. As an example of the digitized results, Fig. 2 presents the accuracy plot for the model of the SG6040 airfoil, which was the least accurate from the four models used in these tests. The average accuracy of the SG6040 airfoil model is, nevertheless, 0.23 mm (0.0089 in) over the 305 mm (12 in) chord. Similar plots for the primary airfoils can be found in Ref. 17. The airfoil coordinates are tabulated in the Appendix.

The lift was directly measured using a strain-gage load cell, and the drag was determined from the average of four different spanwise wake surveys spaced 76.2 mm (3 in) apart.^{15,16} The overall uncertainty in both the lift and drag measurements was estimated to be 1.5%.^{14–16} All measurements were corrected for wind-tunnel interference effects according to a method that has been validated with data from the NASA Langley Low Turbulence Pressure Tunnel.^{17,18} Finally, to simulate leading-edge roughness effects, a 0.58 mm (0.023 in) zigzag trip was fixed to the upper and lower surface of the airfoils.¹⁶ In this paper, this trip size is referred to as the “standard” trip height. The trips were positioned in the vicinity of the suction peaks at 2% chord on the upper surface and at 5% chord on the lower surface. Note that transition does not occur immediately behind the trips but rather takes place over a finite distance.¹⁸ The use of trips instead of grit roughness elements has the advantage of being a more repeatable method, but the results obtained with the standard trips should be considered as a worst case scenario.

IV. WIND TUNNEL TEST RESULTS

This section provides an overview of the airfoil data obtained from the wind-tunnel tests conducted with the four new airfoils. The complete data set can be found in Ref. 16.

Tests with free transition (no trips applied to the airfoil) were conducted at six Reynolds numbers from 100,000 to 500,000. Figures 3 and 4 present the drag polars and corresponding lift curves for the root and primary airfoils, respectively. These figures show that the design objectives have been met. For example, the maximum lift-to-drag ratio of the SG6042 occurs indeed near a lift coefficient of 0.9 at its design Reynolds number and also over most of the Reynolds number range considered. Furthermore, the objective of providing a range of lift coefficients for which best lift-to-drag ratio performance occurs has also been satisfied. Therefore, performance penalties owing to off-design conditions should be relatively small except for a Reynolds number of 100,000 where laminar separation effects caused a large reduction in the drag bucket. It should be emphasized, however, that such performance at a Reynolds number of 100,000 is typical of most low Reynolds airfoils.^{8,15}

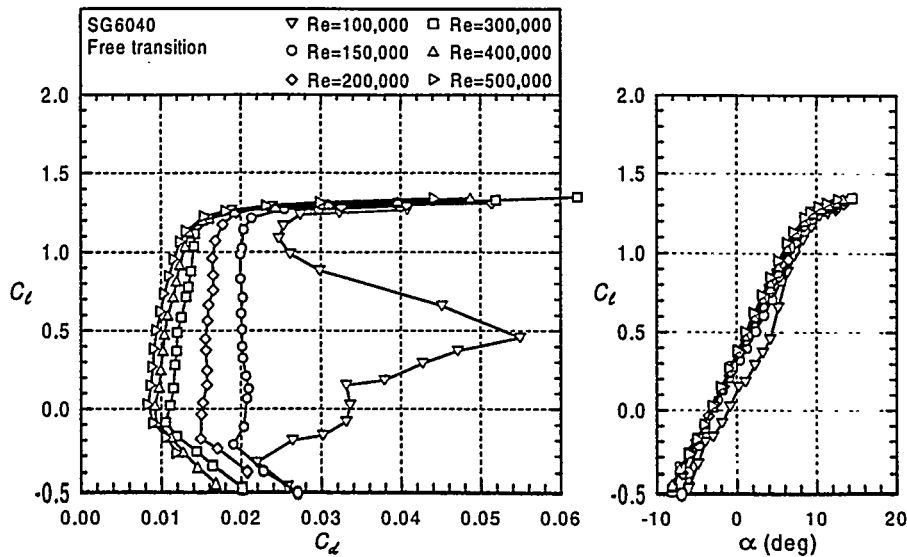


Fig. 3 Drag polars and corresponding lift curves for the SG6040 root airfoil (free transition).

Figure 5 indicates the maximum lift-to-drag ratio and corresponding lift coefficient under clean conditions of the SG604x airfoil family and other low Reynolds number airfoils applicable to small HAWTs.⁸ The results are shown for a Reynolds number of 300,000, which is representative of the data for other Reynolds numbers, and the airfoil thickness of each airfoil is also shown. As indicated in Fig. 5, the new airfoils provide lift-to-drag ratios that are equivalent or exceeding those of previously existing low Reynolds airfoils over a wide range of design lift coefficient. Therefore, small variable-speed HAWTs are likely to benefit from enhanced energy capture from the use of the new airfoils. Note, however, that comparing data for constant Reynolds number can be misleading based on the previously mentioned tradeoff between operating lift coefficient and Reynolds number. A better figure of merit to use in comparing the airfoils would be the maximum lift-to-drag ratio for a given reduced Reynolds number.¹⁰ Nonetheless, the results shown in Fig. 5 are indicative of the potential of the new airfoils for small variable-speed wind turbines.

For the tests with “fixed” transition, three Reynolds numbers were considered for each airfoil: 150,000, 300,000, and 500,000. An overview of these results is shown in Fig. 6 with results for a Reynolds number of 300,000. To facilitate comparison, the drag polar of each airfoil is shown for both free and fixed transition. In these tests, the standard trip as defined in section III was used. As expected, the higher the design lift coefficient and relative thickness of the airfoil, the higher is the loss in performance caused by forcing transition. Furthermore, the lift coefficient corresponding to the maximum lift-to-drag ratio is also influenced by the simulated roughness at the leading edge. The change in lift coefficient for maximum lift-to-drag ratio can be explained by the results presented in Fig. 7. Even though the lift coefficients for maximum lift-to-drag ratio vary between the free and fixed transition cases, Fig. 7 indicates that the angle of attack for which maximum lift-to-drag ratio occurs remains, however, relatively constant. Therefore, a blade designed with the new airfoils should yield optimum performance even with leading-edge roughness. Based on the loss in maximum lift coefficient shown in Fig. 7, the use of the new airfoils should not be extended to small stall-regulated HAWTs. Airfoils such as the NREL S822

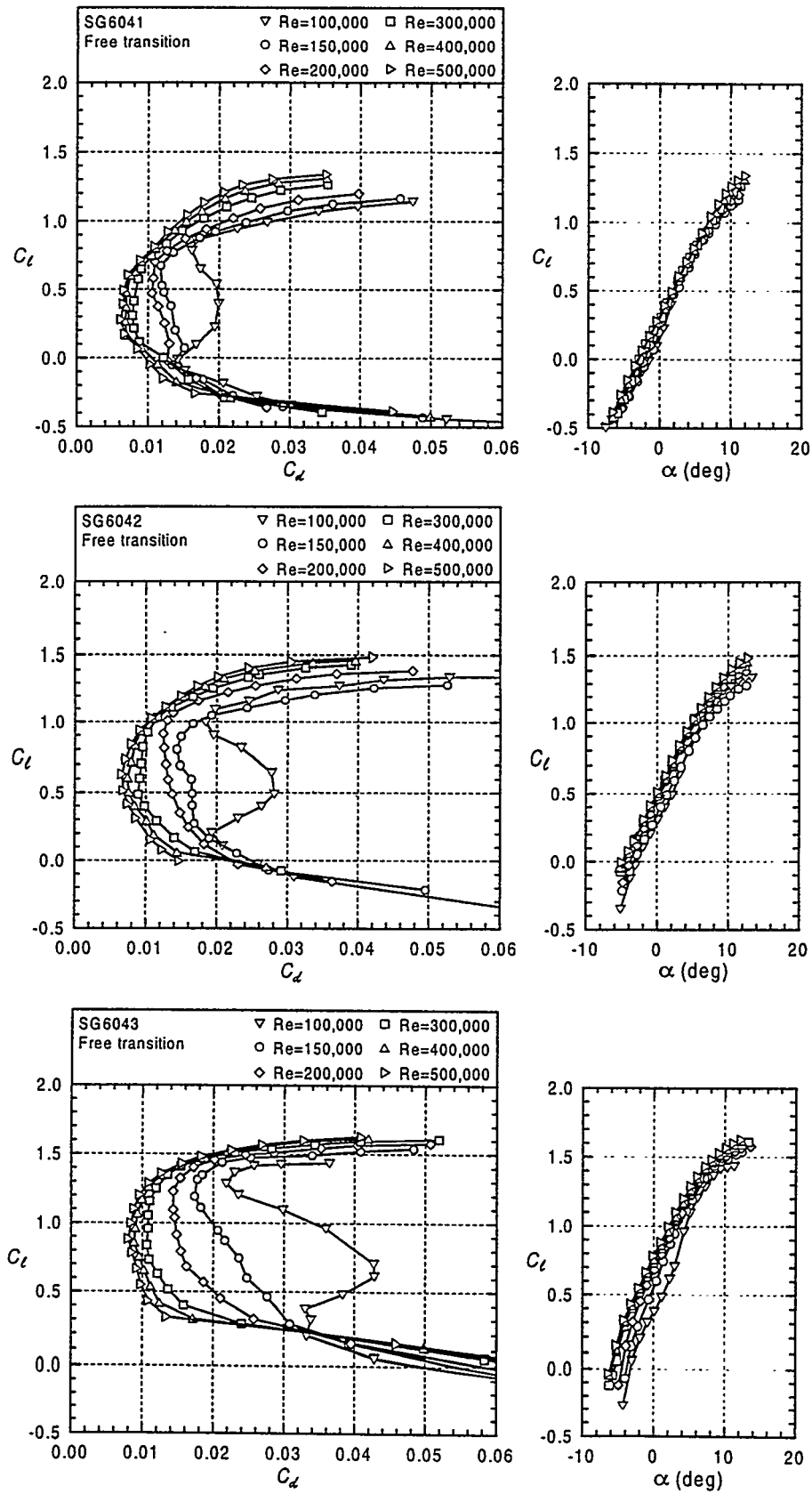


Fig. 4 Drag polars and corresponding lift curves for the primary SG6041, SG6042 and SG6043 airfoils (free transition).

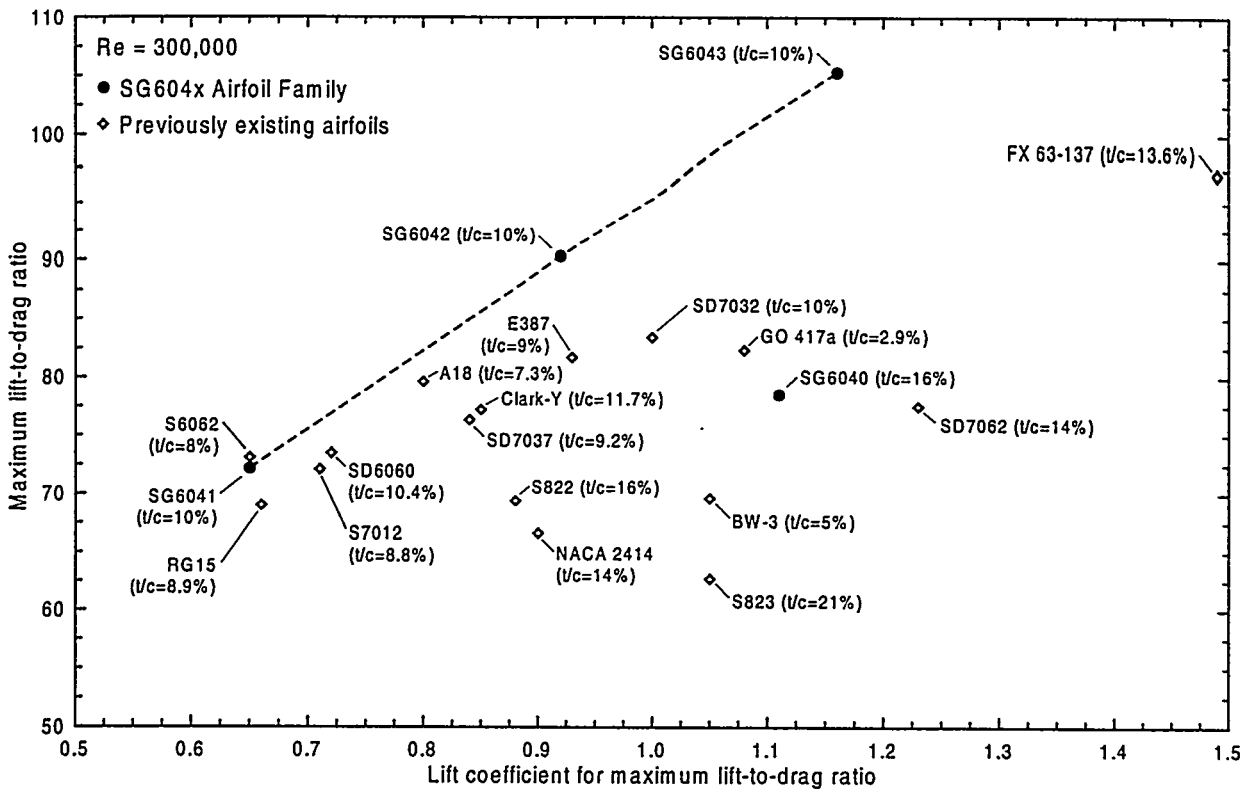


Fig. 5 Maximum lift-to-drag ratio versus the corresponding lift coefficient of various airfoils for small HAWTs at a Reynolds number of 300,000.

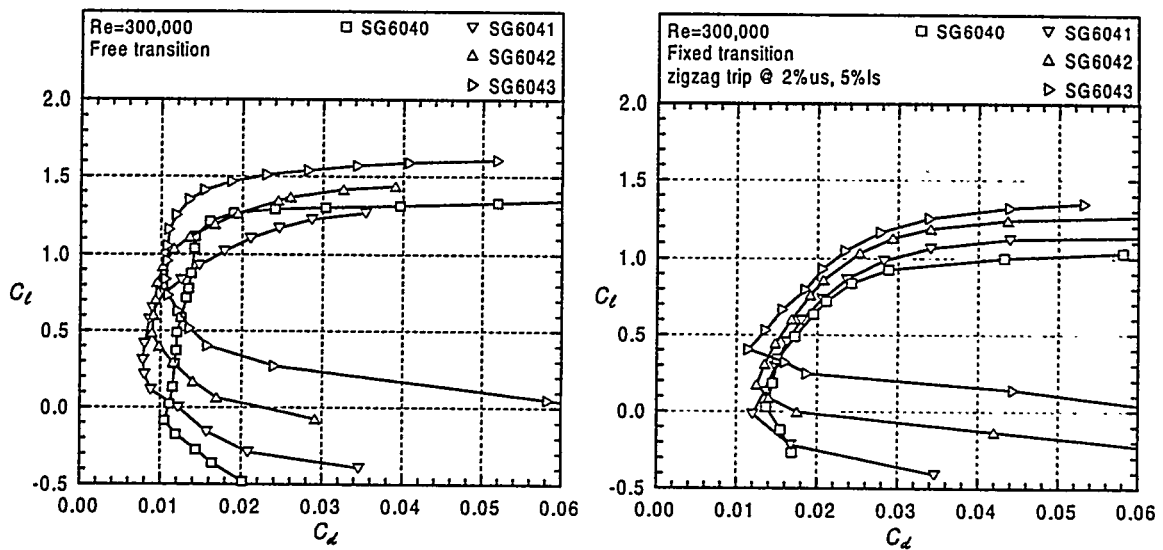


Fig. 6 Drag polars for the root and the primary airfoils at a Reynolds number of 300,000 (free and fixed transition).

and S823 are better candidates in that case. The new airfoils, however, provide much better lift-to-drag ratio performance as compared with the S822 and S823 airfoils.

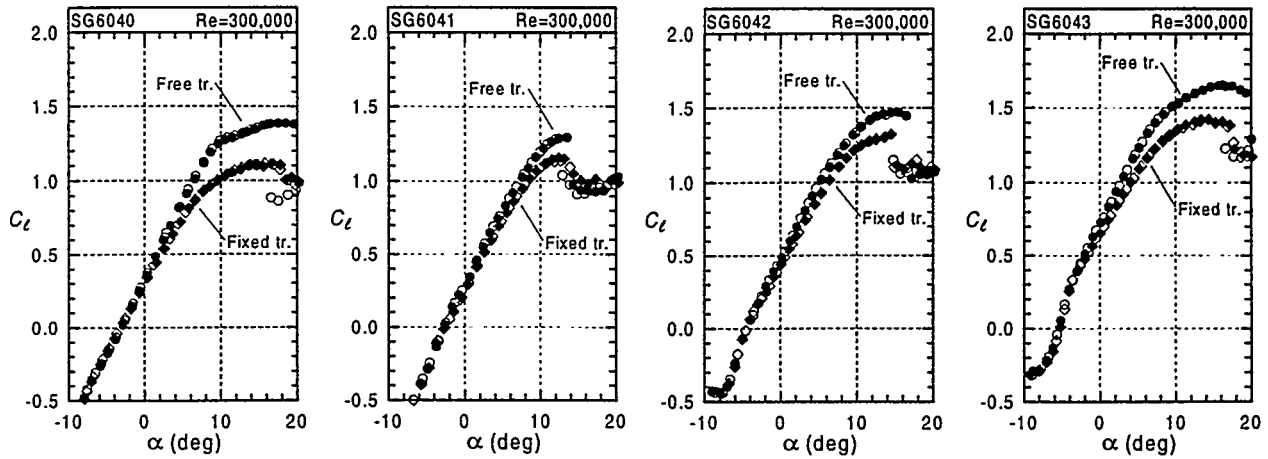


Fig. 7 Lift curves for the root and the primary airfoils at their design Reynolds numbers (free and fixed transition): dark symbols, increasing α and open symbols, decreasing α .

Table 2 Performance summary for the SG604x airfoil family.

SG6040 (root airfoil)							SG6041 (primary airfoil)					
Re	Free transition			Fixed transition			Free transition			Fixed transition		
	C_{lmax}	$C_l; (l/d)_{max}$	$(l/d)_{max}$	C_{lmax}	$C_l; (l/d)_{max}$	$(l/d)_{max}$	C_{lmax}	$C_l; (l/d)_{max}$	$(l/d)_{max}$	C_{lmax}	$C_l; (l/d)_{max}$	$(l/d)_{max}$
100,000	1.29	1.16	46.0	1.08	-	-	1.15	0.86	51.5	1.08	-	-
150,000	1.33	1.21	57.0	1.09	0.70	33.1	1.16	0.67	57.5	1.09	0.80	33.3
200,000	1.35	1.17	66.3	1.09	-	-	1.22	0.70	64.1	1.14	-	-
300,000	1.39	1.11	78.5	1.11	0.84	34.7	1.29	0.65	72.2	1.16	0.87	36.7
400,000	1.42	1.13	83.5	1.13	-	-	1.34	0.60	80.0	1.19	-	-
500,000	1.42	1.13	86.6	1.14	0.76	36.7	1.36	0.61	84.4	1.20	0.77	39.4

SG6042 (primary airfoil)							SG6043 (primary airfoil)					
Re	Free transition			Fixed transition			Free transition			Fixed transition		
	C_{lmax}	$C_l; (l/d)_{max}$	$(l/d)_{max}$	C_{lmax}	$C_l; (l/d)_{max}$	$(l/d)_{max}$	C_{lmax}	$C_l; (l/d)_{max}$	$(l/d)_{max}$	C_{lmax}	$C_l; (l/d)_{max}$	$(l/d)_{max}$
100,000	1.35	1.10	55.6	1.26	-	-	1.52	1.37	59.4	1.36	-	-
150,000	1.29	0.89	59.7	1.27	0.83	38.7	1.56	1.31	74.2	1.38	1.01	42.0
200,000	1.41	1.01	77.8	1.28	-	-	1.59	1.33	86.6	1.40	-	-
300,000	1.47	0.92	90.3	1.32	0.86	41.5	1.65	1.16	105.3	1.42	0.93	45.2
400,000	1.50	0.93	101.0	1.33	-	-	1.68	1.17	118.0	1.44	-	-
500,000	1.52	0.84	105.9	1.34	0.90	45.7	1.70	1.10-1.20	125.1	1.43	0.98	48.4

Table 2 summarizes the maximum lift coefficient, maximum lift-to-drag ratio and the corresponding lift coefficient for both the free and fixed transition cases of the SG604x airfoil family. As expected, the results presented in Table 2 indicate that the sensitivity to roughness of the airfoil performance increases with the design lift coefficient.⁹ Note, however, that for a given Reynolds number, the maximum lift-to-drag ratios with fixed transition of the airfoil having the highest design lift coefficient (SG6043) remain the largest of all the new airfoils. In addition, the lift-to-drag ratio characteristics of the airfoils with fixed transition are for the most part independent of the Reynolds number. Consequently, blades using the SG6043 airfoil are likely to yield the best energy capture in the presence of

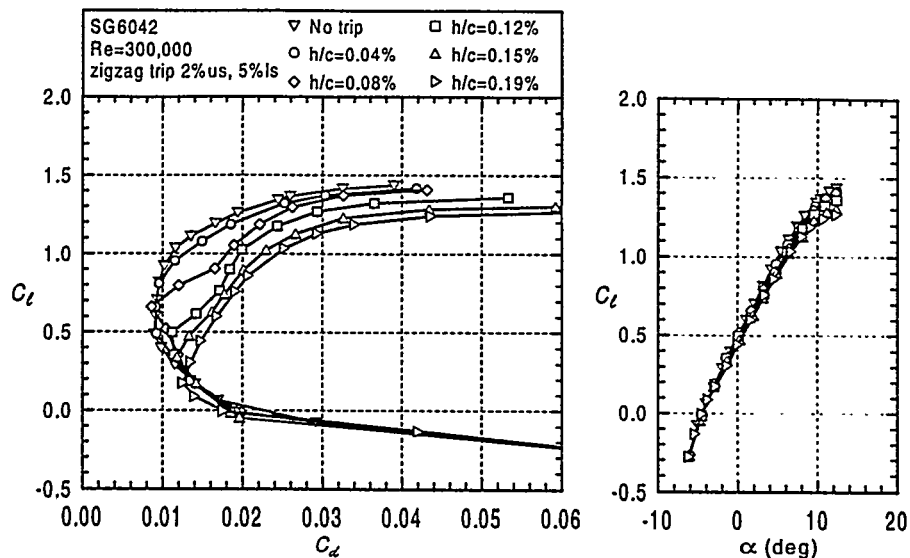


Fig. 8 Drag polars and corresponding lift curves for the SG6042 airfoil with varying zigzag trip heights.

leading-edge roughness elements. Such blades, however, are also likely to be most affected by Reynolds number effects owing to the high design lift coefficient of the SG6043 airfoil.

The data shown so far with fixed transition has been for a fixed trip height, namely the standard trip. The effect of reducing the height of the trip was also investigated, and the results for the SG6042 airfoil at a Reynolds number of 300,000 are shown in Fig. 8. A total of five different zigzag trip heights were used ranging from 0.13 mm (0.005 in) or 0.04% chord to 0.56 mm (0.023 in – standard trip) or 0.19% chord. The results indicate that trips thicker than the smallest one caused a rapid degradation in airfoil performance. Consequently, if leading-edge tape is used on blades making use of the new airfoils, only a very thin layer should be applied.

Further tests were performed with plain trips to investigate whether or not the new airfoils were optimized for low drag at their respective design points. The tradeoff to consider involves reducing bubble drag at the cost of increased device drag — drag caused by the trip itself. For the SG6042 airfoil, a 0.15 mm (0.006 in) thick plain (tape type) trip was positioned at different chordwise positions on the upper surface at the respective design lift coefficient. The results shown in Fig. 9 clearly indicate that the addition of the plain trip did not lead to any drag reduction beyond the experimental uncertainty of the measurements. In addition, three additional plain trip heights were also tested at 35% chord and the same Reynolds number of 300,000. As indicated in Fig. 10, trips thicker than the baseline (0.15 mm) were not beneficial in reducing the overall drag. Similar results were also obtained for the SG6043 airfoil at Reynolds numbers of 200,000 and 300,000. Therefore, the airfoils do have low bubble drag that likely cannot be reduced through the use of a trip or turbulator. Finally, the four airfoils considered as a group provide excellent lift-to-drag ratios over a broad range of lift conditions and are well suited for their intended application.

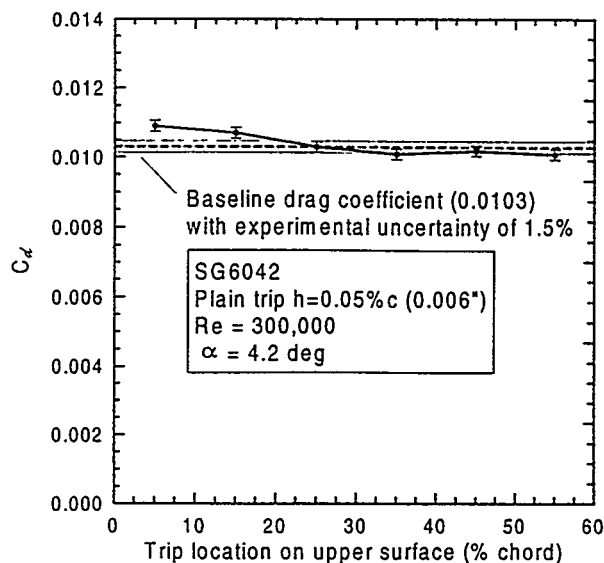


Fig. 9 Drag coefficient as a function of the chordwise position of a $h/c = 0.05\%$ plain trip on the upper surface.

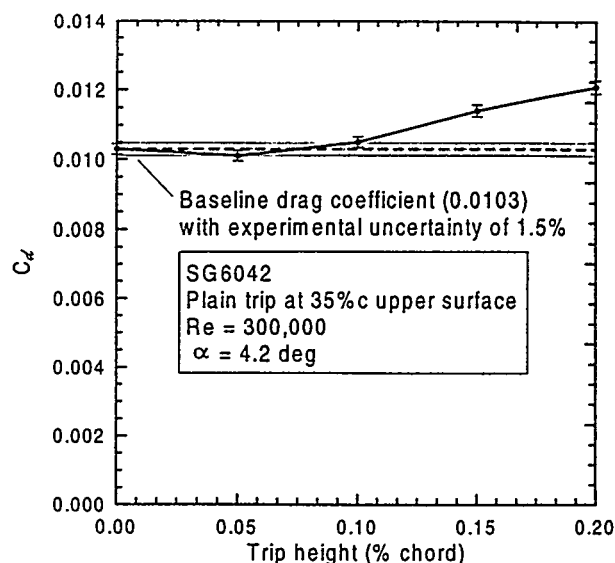


Fig. 10 Drag coefficient as a function of the normalized height of a plain trip positioned at 35% chord on the upper surface.

V. CONCLUSIONS

The airfoils designed during this work form a unique airfoil family for small variable-speed HAWTs. Wind-tunnel tests of the root airfoil (SG6040) and three primary airfoils (SG6041, SG6042 and SG6043) provided an extensive airfoil data set that can be used in the design of small blades. The two primary airfoils having the highest design lift coefficients (SG6042 and SG6043) yielded enhanced lift-to-drag performance over many other low Reynolds number airfoils. Consequently, small variable-speed wind turbines are likely to benefit from the use of these two airfoils. The SG6040 root airfoil and low-lift SG6041 airfoil are also likely to enhance the energy capture of small variable-speed HAWTs owing to structural requirements and the tradeoff between operating lift coefficient and Reynolds numbers. Overall, the new airfoils provide excellent lift-to-drag ratios over a broad range of lift conditions and are well suited for small variable-speed wind turbines.

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APPENDIX: Airfoil Coordinates

SG6040	
x/c	y/c
1.00000	0.00000
0.99788	0.00048
0.99183	0.00207
0.98233	0.00477
0.96977	0.00845
0.95442	0.01283
0.93637	0.01766
0.91559	0.02285
0.89221	0.02845
0.86647	0.03446
0.83861	0.04080
0.80887	0.04739
0.77752	0.05415
0.74482	0.06094
0.71104	0.06759
0.67632	0.07394
0.64081	0.07992
0.60477	0.08541
0.56837	0.09032
0.53180	0.09461
0.49526	0.09815
0.45891	0.10089
0.42297	0.10279
0.38758	0.10378
0.35286	0.10386
0.31903	0.10299
0.28619	0.10116
0.25449	0.09843
0.22405	0.09479
0.19496	0.09028
0.16734	0.08506
0.14137	0.07921
0.11719	0.07283
0.09496	0.06598
0.07481	0.05875
0.05686	0.05123
0.04123	0.04347
0.02798	0.03559
0.01725	0.02771
0.00913	0.01987
0.00362	0.01212
0.00072	0.00449
0.00027	-0.00268
0.00289	-0.00884
0.00906	-0.01450
0.01829	-0.02023
0.03027	-0.02580
0.04483	-0.03103
0.06202	-0.03566
0.08193	-0.03971
0.10446	-0.04336
0.12939	-0.04657
0.15655	-0.04937
0.18574	-0.05172
0.21677	-0.05361
0.24943	-0.05503
0.28349	-0.05594
0.31873	-0.05632
0.35490	-0.05613
0.39177	-0.05528
0.42916	-0.05371
0.46691	-0.05132
0.50479	-0.04801
0.54298	-0.04368
0.58164	-0.03863
0.62049	-0.03323
0.65925	-0.02772
0.69762	-0.02231
0.73526	-0.01718
0.77181	-0.01250
0.80690	-0.00840
0.84016	-0.00497
0.87120	-0.00228
0.89963	-0.00033
0.92511	0.00090
0.94728	0.00148
0.96587	0.00154
0.98063	0.00122
0.99132	0.00070
0.99782	0.00022
1.00000	0.00000

SG6041	
x/c	y/c
1.00000	0.00000
0.99801	0.00029
0.99227	0.00132
0.98311	0.00310
0.97084	0.00560
0.95568	0.00867
0.93778	0.01217
0.91722	0.01600
0.89412	0.02018
0.86872	0.02469
0.84127	0.02946
0.81200	0.03438
0.78119	0.03933
0.74901	0.04408
0.71552	0.04849
0.68087	0.05261
0.64526	0.05635
0.60884	0.05967
0.57186	0.06258
0.53448	0.06502
0.49692	0.06699
0.45939	0.06847
0.42211	0.06944
0.38529	0.06991
0.34915	0.06987
0.31389	0.06931
0.27971	0.06824
0.24683	0.06666
0.21540	0.06458
0.18563	0.06201
0.15767	0.05896
0.13169	0.05546
0.10783	0.05149
0.08618	0.04710
0.06690	0.04231
0.05002	0.03711
0.03555	0.03159
0.02361	0.02578
0.01411	0.01971
0.00702	0.01366
0.00241	0.00767
0.00016	0.00194
0.00029	-0.00229
0.00378	-0.00645
0.01080	-0.01010
0.02073	-0.01346
0.03361	-0.01637
0.04948	-0.01888
0.06829	-0.02104
0.08990	-0.02294
0.11413	-0.02461
0.14081	-0.02605
0.16976	-0.02728
0.20077	-0.02828
0.23363	-0.02907
0.26812	-0.02964
0.30402	-0.02998
0.34108	-0.03010
0.37907	-0.02997
0.41772	-0.02959
0.45679	-0.02894
0.49604	-0.02797
0.53524	-0.02663
0.57423	-0.02493
0.61284	-0.02285
0.65090	-0.02037
0.68832	-0.01763
0.72492	-0.01482
0.76041	-0.01210
0.79448	-0.00956
0.82683	-0.00728
0.85718	-0.00532
0.88524	-0.00370
0.91073	-0.00243
0.93339	-0.00149
0.95300	-0.00083
0.96938	-0.00036
0.98244	-0.00005
0.99204	0.00008
0.99798	0.00006
1.00000	0.00000

SG6042	
x/c	y/c
1.00000	0.00000
0.99806	0.00048
0.99249	0.00203
0.98372	0.00463
0.97210	0.00811
0.95784	0.01223
0.94102	0.01672
0.92161	0.02148
0.89968	0.02657
0.87546	0.03195
0.84915	0.03756
0.82098	0.04333
0.79117	0.04914
0.75995	0.05489
0.72757	0.06038
0.69410	0.06544
0.65962	0.07006
0.62435	0.07417
0.58844	0.07772
0.55208	0.08071
0.51546	0.08310
0.47877	0.08486
0.44221	0.08600
0.40597	0.08648
0.37024	0.08634
0.33522	0.08556
0.30110	0.08415
0.26808	0.08215
0.23633	0.07956
0.20603	0.07639
0.17735	0.07269
0.15044	0.06847
0.12544	0.06379
0.10249	0.05866
0.08169	0.05313
0.06316	0.04726
0.04698	0.04105
0.03315	0.03458
0.02179	0.02795
0.01284	0.02119
0.00619	0.01446
0.00197	0.00797
0.00011	0.00182
0.00035	-0.00341
0.00371	-0.00730
0.01068	-0.01042
0.02068	-0.01311
0.03369	-0.01516
0.04982	-0.01659
0.06901	-0.01751
0.09117	-0.01805
0.11611	-0.01826
0.14365	-0.01821
0.17358	-0.01792
0.20570	-0.01744
0.23979	-0.01679
0.27559	-0.01599
0.31286	-0.01506
0.35135	-0.01401
0.39078	-0.01286
0.43089	-0.01159
0.47140	-0.01016
0.51208	-0.00853
0.55277	-0.00671
0.59330	-0.00475
0.63345	-0.00273
0.67298	-0.00077
0.71161	0.00102
0.74904	0.00255
0.78494	0.00377
0.81900	0.00462
0.85093	0.00510
0.88041	0.00521
0.90718	0.00496
0.93097	0.00442
0.95153	0.00364
0.96868	0.00273
0.98224	0.00178
0.99204	0.00090
0.99800	0.00026
1.00000	0.00000

SG6043	
x/c	y/c
1.00000	0.00000
0.99811	0.00066
0.99274	0.00271
0.98439	0.00607
0.97343	0.01047
0.96007	0.01552
0.94429	0.02092
0.92597	0.02655
0.90516	0.03248
0.88207	0.03868
0.85688	0.04510
0.82979	0.05165
0.80101	0.05824
0.77074	0.06478
0.73922	0.07114
0.70666	0.07717
0.67320	0.08268
0.63889	0.08761
0.60396	0.09190
0.56854	0.09551
0.53276	0.09842
0.49685	0.10059
0.46096	0.10201
0.42528	0.10269
0.39000	0.10260
0.35527	0.10175
0.32131	0.10017
0.28827	0.09788
0.25633	0.09491
0.22567	0.09127
0.19645	0.08702
0.16882	0.08220
0.14293	0.07684
0.11890	0.07100
0.09687	0.06473
0.07694	0.05809
0.05920	0.05117
0.04376	0.04398
0.03062	0.03659
0.01983	0.02916
0.01142	0.02171
0.00528	0.01436
0.00150	0.00741
0.00002	0.00094
0.00059	-0.00468
0.00393	-0.00860
0.01077	-0.01120
0.02087	-0.01316
0.03409	-0.01430
0.05050	-0.01460
0.07015	-0.01422
0.09292	-0.01329
0.11864	-0.01197
0.14712	-0.01034
0.17815	-0.00848
0.21150	-0.00645
0.24693	-0.00430
0.28417	-0.00210
0.32296	0.00011
0.36301	0.00232
0.40401	0.00450
0.44571	0.00669
0.48785	0.00893
0.53029	0.01117
0.57286	0.01327
0.61525	0.01504
0.65704	0.01635
0.69785	0.01721
0.73735	0.01760
0.77520	0.01751
0.81109	0.01695
0.84468	0.01592
0.87567	0.01447
0.90377	0.01265
0.92871	0.01056
0.95024	0.00828
0.96814	0.00591
0.98215	0.00361
0.99209	0.00170
0.99803	0.00045
1.00000	0.00000

INITIAL RESULTS FROM THE OPERATION OF VILLAGE HYBRID SYSTEMS IN CHILE

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ABSTRACT

The government of Chile has undertaken a rural electrification program to electrify 75% of the population by the year 2000. Renewable energy is considered within this program, and its application facilitated through a technical cooperation agreement between Chile's national energy commission (CNE) and the U.S. Department of Energy. In order to introduce isolated mini-grid hybrid wind-energy systems into Chile, three pilot projects were implemented in Region IX. The goal of the pilot systems is to establish renewables as a viable option for rural electrification in the Chilean context.

In this paper we report on the first six months of operation of three pilot projects. Presented as background information are brief descriptions of the power systems, data acquisition systems, and the operation and maintenance (O&M) protocols. Analyses of loads, component performance, system operation, and balance of payments for O&M are the primary points presented. Important lessons learned and future plans are also discussed.

INTRODUCTION

In October 1994, the U.S. Department of Energy (USDOE) and the National Energy Commission of Chile (CNE) signed a technical cooperation agreement for the implementation of renewable energy in rural electrification projects within the framework of the Chilean Rural Electrification Program (PER). The goal of the PER is to have 75% electrification in the rural areas of Chile by the year 2000. This goal is to be met through a process of partial project funding from the FNDR (National Fund for Regional Development) at the national level, project selection by the regional authorities (SERPLAC), and implementation by private enterprises.

In December 1995, the SERPLAC of Region IX and a private electricity distribution company, SAESA/Frontel, signed an agreement to implement hybrid wind-energy projects in Region IX for purposes of demonstration of an alternative solution to line extension. Region IX (shown in Figure 1) is characterized by having the most unelectrified homes of all twelve regions in Chile, a good wind resource all year, and a poor solar resource in winter. The Region IX *pilot projects* are intended to: (1) demonstrate that isolated mini-grids powered by hybrid wind-energy systems are technically and economically viable alternatives to grid extension and solar home systems and, consequently, encourage replication in Regions VI through XI; (2) start the building of an infrastructure and knowledge base in

Chile for designing and supporting such projects; and (3) provide information and data to improve the design of future projects. The pilot projects were funded in the same way that future projects will be; that is, the bulk of the cost (50-100%) is subsidized by the FNDR while the remainder comes from direct contributions of the implementing enterprise (10-25%) and income from consumer tariffs (5-25%). The subsidy for each project is fixed at a level which allows the implementing enterprise to at least break even over 30 years. In the case of the pilot projects, half of the FNDR subsidy was provided by USDOE in the form of the renewable energy components of the systems.

There are three pilot project sites in Region IX - Puaucho, Isla Nahuel Huapi, and Villa Las Araucarias (see Figure 1). Puaucho (PUA) is a small hamlet on a hill overlooking the Pacific Ocean. The modest electric load at Puaucho consists of a regional school, a health post, and three residences. The national electric grid is expected to arrive at Puaucho sometime in 1998 and, at that time, the hybrid system will be moved to a different site. Isla Nahuel Huapi (INH) is a small island in Budi Lake, just inland of the Pacific Ocean. It has a health post and 11 residences. Villa Las Araucarias (VLA) is located in a relatively flat area on the top of a coastal mountain range at approximately 800 meters above sea level. This site presently has an area school, health post, church, forestry office, and 17 residences. Due to an ongoing resettlement project, it is possible that the number of residences at VLA could double in the near future.

Work on the pilot projects began in January 1996 and all three systems were commissioned in January of 1997. Commissioning was delayed about 6 months due to a number of factors including equipment importation problems, wind turbine tower fabrication delays, weather-related installation delays, and a lengthy tariff setting process. To date all systems have been running for about 6 months. The purpose of this paper is to describe those first 6 months of operation and share the lessons learned from these "first-of-a-kind" systems in Chile.

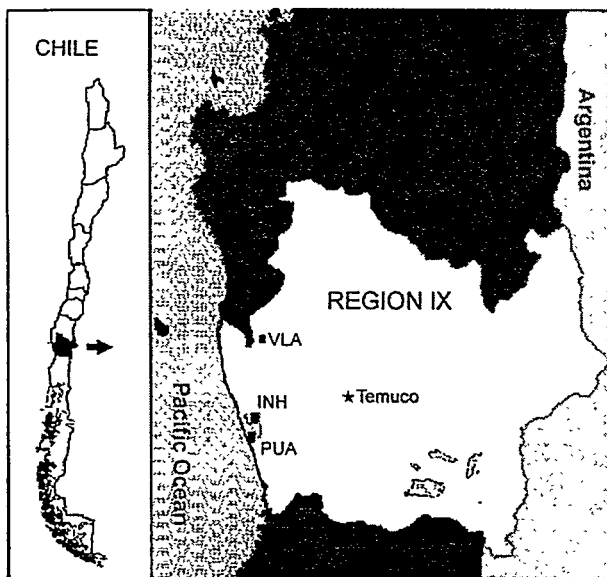


FIGURE 1. REGION IX OF CHILE WITH PILOT PROJECT SITES AND ITS CAPITAL, TEMUCO.

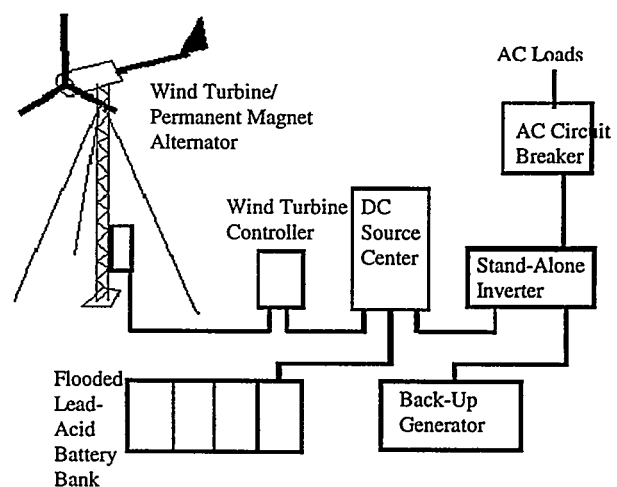


FIGURE 2. GENERAL HYBRID SYSTEM ARCHITECTURE USED IN CHILE

SYSTEM ARCHITECTURE

Each of the hybrid power systems consists of a permanent magnet wind turbine generator, wind turbine rectifier/controller, DC source center, stand-alone inverter, flooded lead-acid battery bank, and a back-up generator as shown in Figure 2. The specific components in each system differ somewhat due to the differing village loads and the need to demonstrate different types of equipment. The power system equipment was placed in a small shelter at the base of the turbine towers. The shelter was divided into three separate compartments for the generator, batteries, and power electronics. The distribution system is a bare copper, 2-wire line and pole system carrying 220 Vac, 50 Hz to the individual buildings. The electricity use is metered in the shelter and at each termination in the distribution system. The longest distribution runs range from 300 meters at Puaucho to about 1,300 meters at Isla Nahuel Huapi.

Table 1 shows the major equipment used at each site. Bergey Windpower Company (BWC) of Norman, Oklahoma and World Power Technologies (WPT) of Duluth, Minnesota provided the wind turbines and rectifier/controllers. The two BWC wind turbines are three-bladed and the WPT turbine is two-bladed. All turbines are mounted on locally-fabricated, 24-meter, guyed, tilt-up towers. Step-down transformers are located between the turbine and controller at Isla Nahuel Huapi and Villa Las Araucarias.

Two different models of Trace (Arlington, Washington) inverter were used. The DR series produces a modified-sine output and the SW series produces a true-sine output. The SW series also incorporates very sophisticated controls including automatic generator start-up. At Puaucho, the generator must be started manually. Two types of Trojan (Santa Fe Springs, California) flooded lead-acid, deep-cycle batteries are used: the T-105 (200 amp-hour) and L-16 (350 amp-hour). Both batteries are available from distributors in Santiago, Chile. The Honda gasoline generators were also purchased from a distributor in Santiago. All three generators are nominally 3.8 kW with the two at INH and VLA having an electric start circuit. A 100-liter reserve fuel tank is included in each system. The DC source centers included fuse and/or circuit breaker protection and manual disconnects for the batteries, controller, and inverter. The systems at PUA and INH utilize fuses and disconnects which were purchased and assembled in Chile while at VLA the DC source center was provided by BWC.

TABLE 1. HYBRID SYSTEM EQUIPMENT

Site	DC Bus Voltage	Wind Turbine	Inverter	Batteries	Generator
Puaucho	24 Vdc	BWC1500 (1.5 kW)	Trace DR2424E (modified sine)	12 Trojan T-105 (14.4 kWh)	Honda EZ4500 (manual start)
Isla Nahuel Huapi	24 Vdc	WPT3000 (3.0 kW)	Trace SW3024E (sine wave)	8 Trojan L-16 (16.8 kWh)	Honda EM4500SX (auto start)
Villa Las Araucarias	48 Vdc	BWC EXCEL (7 kW)	Trace SW3048E (sine wave)	16 Trojan L-16 (33.6 kWh)	Honda EM4500SX (auto start)

DATA ACQUISITION SYSTEM

A data acquisition system (DAS) was installed at each site to meet the aforementioned goals of the pilot projects. More specifically, the DAS will provide data to: (1) determine component and system efficiencies, (2) verify proper system functioning, (3) aid in problem troubleshooting, (4) detect and analyze significant village load changes, and (5) calculate actual cost of utilized energy.

Table 2 summarizes the DAS instrumentation. The measurements are recorded on Campbell Scientific, Inc. (Salt Lake City, Utah) CR10X dataloggers with one megabyte internal memory. The dataloggers are powered by a small sealed lead-acid battery pack which is float charged off of the power system battery bank. Data is sampled every second and then averaged for each hour. The generator on/off status is sampled and recorded every 10 minutes.

TABLE 2. DATA ACQUISITION SYSTEM INSTRUMENTATION

Measurement	Sensor(s)/Instrumentation
Wind Speed (2 heights)	NRG Systems Maximum 40 Anemometer
Wind Direction	NRG Systems 200P Wind Vane
DC Current from Controller	Ohio Semitronics, Inc. CTFB-100TT Current Transducer
DC Current into Inverter	Ohio Semitronics, Inc. CTFB-100TT Current Transducer
DC Bus Voltage	Campbell Scientific, Inc. 20:1 Voltage Divider
Load Real Power	Ohio Semitronics, Inc. PC20-104CX5 Power Transducer, Ohio Semitronics, Inc. 20:1 Current Transformer, and Campbell Scientific, Inc. 2:1 Voltage Divider
Load Power Factor	Same equipment as above for Load Real Power
Generator On/Off Status	NAIS HC2-H-240 Relay
Battery Temperature	Type J Thermocouple

OPERATION AND MAINTENANCE (O&M) PROTOCOL

The ultimate goals for the O&M protocol for these systems are: (1) a utility worker make no more than semi-annual visits to the sites primarily for battery and generator maintenance while the day-to-day affairs of the system are handled by someone in each community, and (2) system failures are reported by the local person in charge and immediately repaired by a qualified specialist. At the present time, however, SAESA/Frontel workers and engineers are responsible for most of the maintenance and repair. While there have already been several training sessions for utility personnel, local operators, and the communities, training is an ongoing process which will continue through 1997. Furthermore, a maintenance manual has been developed and translated into Spanish for these systems, and forms the basis for a routine maintenance program

The maintenance of the systems is broken down into tasks which must be performed on daily to annual intervals. Table 3 summarizes the current maintenance program for the pilot projects. In accordance with the aforementioned goals, the monthly and tri-monthly responsibilities will be eventually transferred to the local operators. Our experience indicates that the local operators are willing and able to take on these expanded responsibilities. This move should make the systems much less expensive to operate for Frontel (cost issues are discussed in more detail in the next section).

At all three sites, there are a few primary rules which govern the operation of these hybrid systems. They are: (1) the battery bank should not be discharged below 20% state-of-charge (SOC) or 1.75 volts per cell (temperature compensated); (2) the generator should run at least 30 minutes every two weeks; (3) the batteries should be equalized at least once every month; and (4) the generator should not be used to finish charge the batteries. The first rule implies two other rules. First, that the batteries be disconnected from the load at 20% SOC and, second, that the generator begins charging the batteries when they reach

TABLE 3. SUMMARY OF MAINTENANCE PROGRAM FOR CHILE PILOT SYSTEMS

Maintenance Interval	Person(s) Responsible	Description
Once per Day	Local Operator	Check generator oil and fuel levels and fill if necessary; Record battery bank voltage; Inform Frontel if there are any problems
Every 15 Days	Local Operator	Run the generator for 1/2 hour; Check generator oil filter
Once per Month	Frontel Worker/Contractor	Check battery specific gravity and electrolyte levels - fill if necessary; Equalize charge battery bank; Clean battery terminals; Visually inspect system for loosened fasteners/connections and signs of overheating; Check generator carburetor
Once per 3 Months	Frontel Worker/Contractor	Clean generator air filter.
Once per 6 Months	Frontel Worker/Contractor	Change generator oil, oil filter, and air filter; Clean generator gas filter; Adjust/clean spark plug.
Once per Year	Frontel Worker/Contractor	Generator maintenance: clean points, change spark plug, adjust valves, check exhaust system, clean fuel tank and fuel line; Climb turbine tower to inspect turbine and anemometers/direction vanes. Inspect distribution system

25% SOC. The fourth rule implies that the generator stop charging the batteries when they reach 80% SOC. The Trace SW series inverters can execute all of the above operations except for automatic periodic equalizations. This is not a problem since the equalizations should involve human intervention in any case, to loosen battery caps and open the doors on the battery compartment. At Puaicho, where the generator operation is manual, the local operator must start the generator after the inverter shuts off due to the low battery condition. The operator in Puaicho seems perfectly amenable to this type of operation.

TARIFFS AND COSTS

One of the most important, yet often controversial, issues of any rural electrification program is cost recovery through tariffs. The paradox is well-known. It is very expensive to provide electricity to remote, sparsely populated areas and yet the people in these areas are usually the least able to afford this service. Consequently, most rural electrification programs require some sort of subsidy, direct or indirect, and these systems in Chile are no exception.

The initial costs of each of the pilot hybrid systems are presented in Table 4. For comparison, the estimated costs of grid extension to each project site are also given. The costs of the local distribution system and the interior wiring are kept separate because they must be added to the costs of both electrification solutions. Hybrid system costs cover all equipment (except the DAS) including spare parts, transportation, fabrication, and installation. Grid extension costs cover the equipment and installation for the transmission line from substation to local step-down transformer.

TABLE 4. COST COMPARISON OF HYBRID SYSTEMS AND GRID EXTENSIONS
(ALL COSTS IN US DOLLAR EQUIVALENTS)

Project Site	Hybrid System	Grid Extension	Distribution/Interior
PUA	\$19,000	\$27,500	\$3,500
INH	\$23,700	\$82,500	\$12,400
VLA	\$36,400	\$110,000	\$11,100

The electricity tariffs charged to the end-users at the three pilot project sites were negotiated between Frontel and the local governments. The tariffs were all structured as follows (all amounts have been converted to US dollar equivalents): fixed monthly charge = US\$1.57; energy charge = US\$0.13 per kWh; distance multiplier (multiplies sum of fixed and energy charges) = 1.25. A household which consumes 10 kWh in a month would be billed $(1.57 + (10)(.13)) \times 1.25$ or US\$3.59 before taxes (a final tax multiplier of 1.18 could be used to determine the actual total electricity bill). The tariff setting process was a long and political one. The result was that the hybrid system users are paying approximately the same tariff that one would pay in this region of Chile for grid service. Small connection charges were paid by the local governments for the people of Puaicho and Isla Nahuel Huapi. At Villa Las Araucarias, the people agreed to pay the connection charge. At projected load levels, each of the communities will generate the following revenues for SAESA/Frontel per month: PUA = US\$30; INH = US\$50; and VLA = US\$90. Currently, the communities generate not more than half of these amounts due to initial low energy consumption and, at VLA, unconnected households.

Figure 3 has been constructed to show the maintenance intervals at which SAESA/Frontel will break even on revenues minus O&M costs. The following items have been incorporated into Figure 3: (1) site visit cost of approximately US\$75 which includes wages for a Frontel worker, transportation to the sites, and costs of miscellaneous parts such as air filters and oil, (2) two unscheduled repair visits by a qualified technician at US\$200 each, (3) cost per liter of gasoline of US\$0.60, (4) "net revenues" equal to the tariff income minus gasoline expenditures for each site, and (5) annual tariff income based on the long-term estimates of the village load.

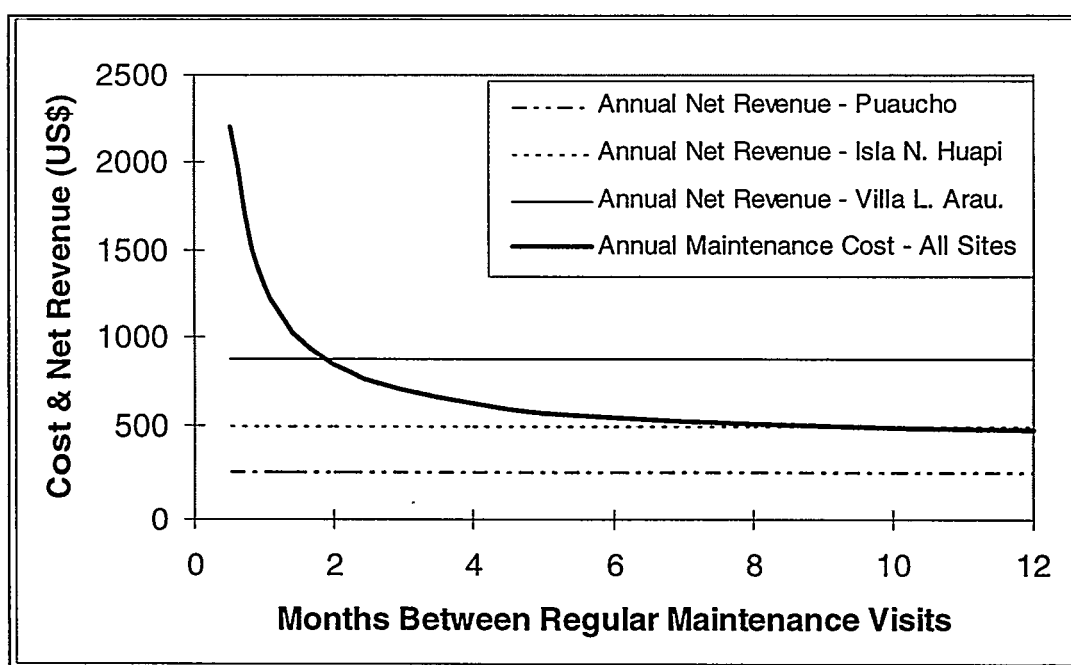


FIGURE 3. NET REVENUES (TARIFF INCOME - FUEL EXPENDITURE) AND MAINTENANCE COSTS (SITE VISITS) FOR CHILE PILOT PROJECTS

The result of Figure 3 is that the minimum time period between regularly-scheduled maintenance visits to the sites should be as follows (on a break-even basis): PUA = more than 12 months; INH = 8 months; and VLA = 2 months. If the actual maintenance interval is stretched to 6 months at all of the sites, SAESA/Frontel could make some profit on these systems if the Puaicho system is moved to a community with higher energy consumption. The battery replacements will be funded by regular tariff increases.

INITIAL OPERATION AND PERFORMANCE RESULTS

The village loads, both energy consumption and peak power demand, were very small. Table 5 summarizes the actual and long-term anticipated loads for all three communities. At all of the sites, 20-watt compact fluorescent lighting presently accounts for the majority of the loads. There are some radios in use as well as a small water pump at Puaicho. Refrigeration in the residences has been discouraged from the outset of the projects. We anticipate that the loads will eventually include televisions, kitchen appliances, more water pumps, and refrigeration for the health posts. The difference in the actual and long-term loads for Villa Las Araucarias is the result of only 9 of 21 buildings being connected. The load shapes shown in Figure 4 have the typical village profile with the pronounced evening peak. An important feature of the load profiles is that a few loads, presumably lights, remain on all day, despite our recommendations to the contrary.

TABLE 5. VILLAGE LOADS - ACTUAL VS. LONG-TERM ANTICIPATED

Site	Actual Monthly Energy Consumption (kWh)	Long-Term Monthly Energy Consumption (kWh)	Actual Peak Demand (Watts)	Long-Term Peak Demand (Watts)
Puaicho	48	120	190	700
Isla Nahuel Huapi	30	153	105	700
Villa L. Araucarias	38	294	205	1200

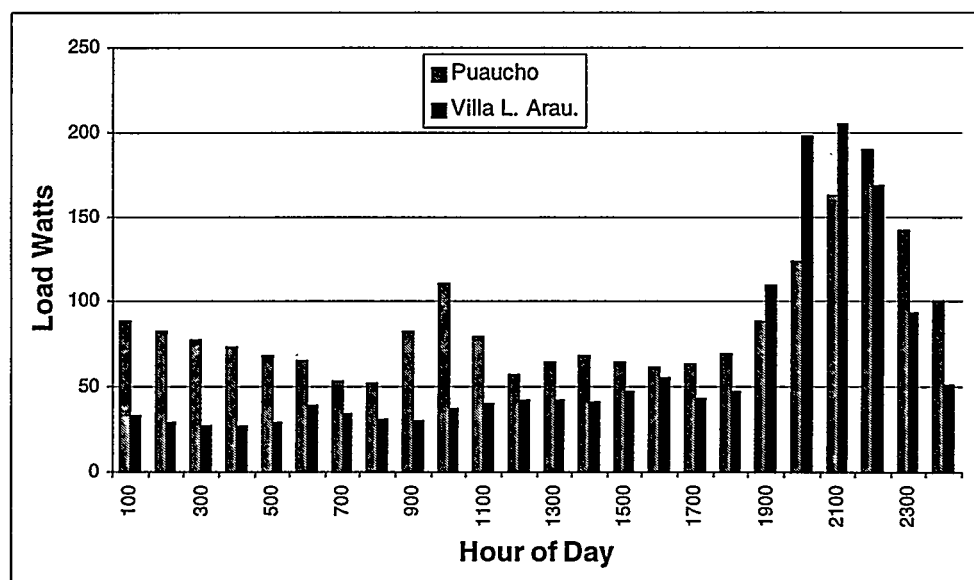


FIGURE 4. AVERAGE DAILY VILLAGE LOAD PROFILES

The battery banks have experienced severe cycling in their first six months of use due to the generator shut-down from overheating, a wind turbine controller dump load failure at Isla Nahuel Huapi, and the annual low wind period in southern Chile March through May. Despite these problems, low loads and sufficient winds between lulls helped to keep the batteries from remaining at a low state-of-charge for long periods (see Figure 5). Due to inadequate ventilation and high March temperatures, the generators were only able to run for 2 or 3 hours before overheating and shutting down. This prevented adequate bulk and equalization charging of the batteries. The lack of equalization charging resulted in battery cell imbalances which further compounded the battery charging problems. The dump load failure at Isla Nahuel Huapi caused the batteries to overcharge at times and to lose excessive amounts of water. It was May before all of these problems were fixed. Quick response to these problems was hampered both by a lack of personnel, fully knowledgeable in hybrid wind systems, and by the lack of suitable replacement parts in this region of Chile. The infrastructure that is developing with these pilot projects will help to prevent such delays in the future.

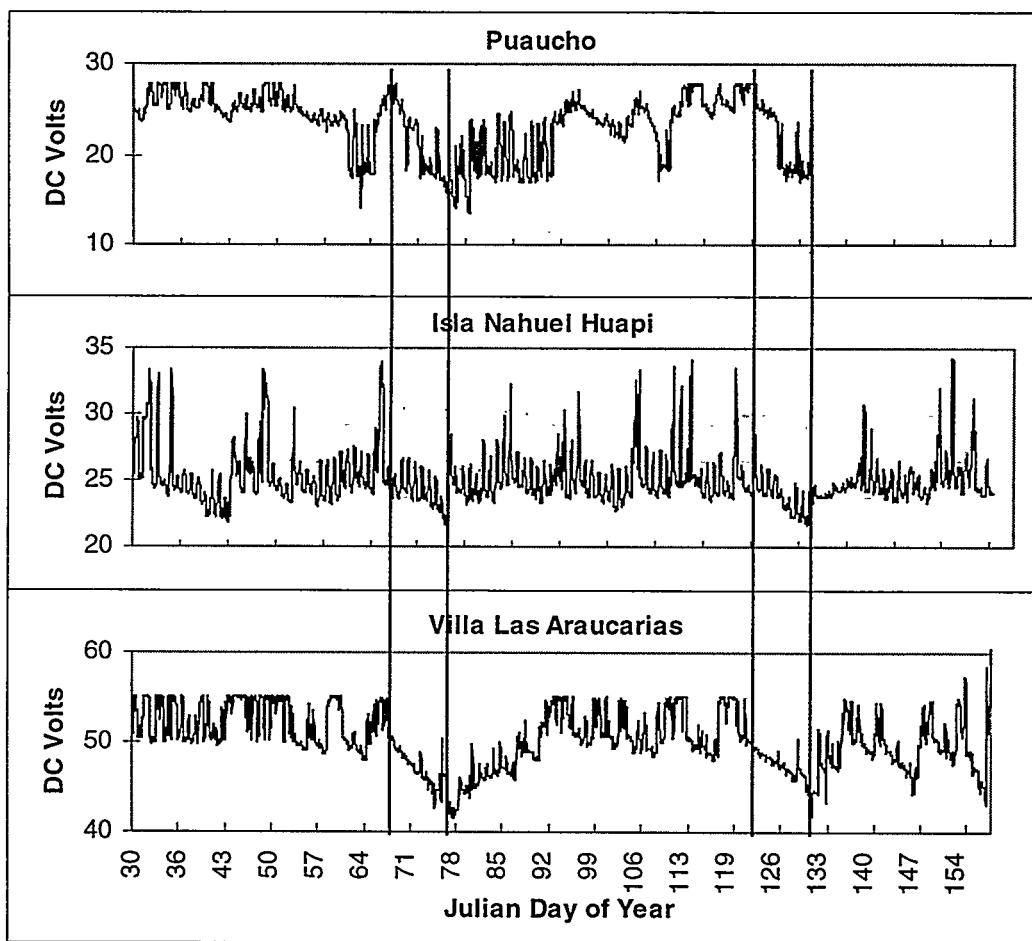


FIGURE 5. DC VOLTAGE HISTORIES WITH WIND LULLS SHOWN BETWEEN THE BARS

Monitoring component outputs and efficiencies is important for two reasons, both of which tie into the goals of maximizing system performance and reducing cost of energy. The first reason is to make sure that the equipment is operating to the manufacturer specifications. The second is to know how the actual operating conditions affect equipment utilization and performance. As an example, Figure 6 shows monthly DC outputs in kilowatt-hours of the BWC 1.5 kW wind turbine at Puaicho compared to its potential output. Due to the small loads and relatively high battery voltages during this initial period, the

output of the turbine fell below its potential due to regulation by the turbine's controller. This under-utilization will improve over time as the village loads increase. We are also investigating the possibility of increasing the size of the battery bank in order to improve wind turbine utilization.

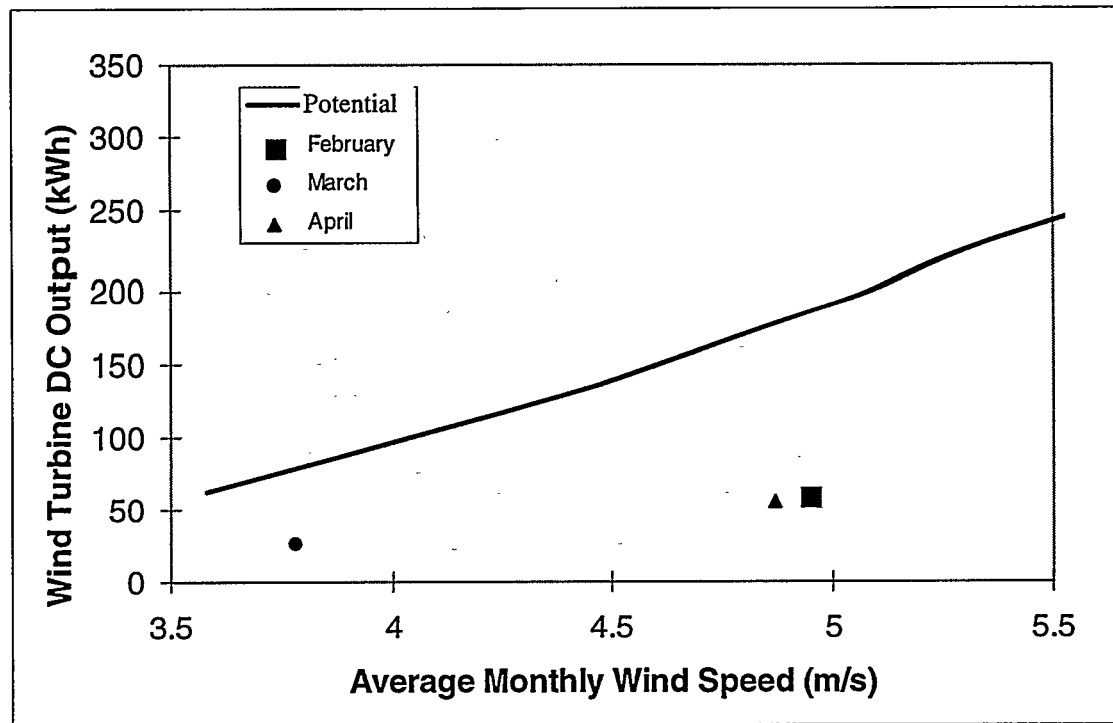


FIGURE 6. DC OUTPUT OF BWC 1500 WIND TURBINE BY MONTH

The data acquisition systems do not determine how efficiently the generators are charging the batteries; however, we have been able to examine the voltage waveforms during generator-to-battery charging with a digital oscilloscope. The charging waveforms produced by the Trace SW series inverters at Villa Las Araucarias and Isla Nahuel Huapi are very close to being true sinewaves. However, the DR series modified-sine inverter at Puaucho produced a flattened sinewave which is shown in Figure 7. By clipping the higher voltages from the generator waveform, the inverter was unable to produce the required 30 volts for equalization. The highest voltage reached was around 27 to 28 volts. Consequently, the batteries must be equalized with the wind turbine. Changing over to this type of operation could have the added benefit of saving fuel.

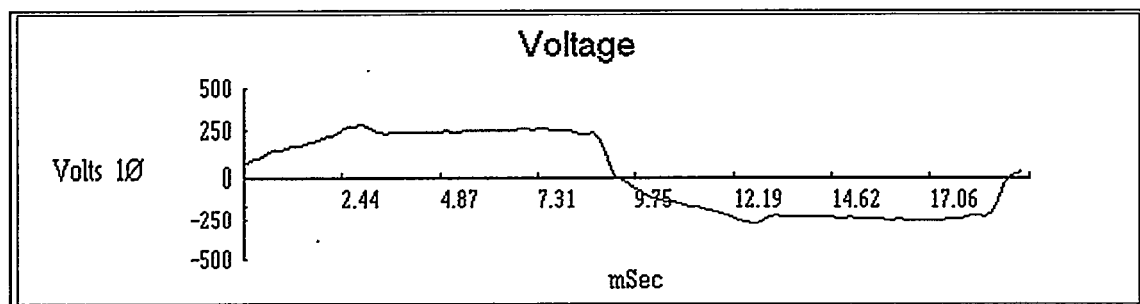


FIGURE 7. WAVEFORM CAPTURED BETWEEN GENERATOR AND INVERTER DURING BATTERY

LESSONS LEARNED AND FUTURE PLANS

The challenges encountered during the initial implementation of the three pilot projects in Region IX can be broadly grouped as follows: (1) minimizing costs while maintaining an acceptable quality of service, (2) setting proper tariffs, (3) providing timely technical assistance, and (4) getting the most local participation possible.

Minimizing cost is necessary for ensuring the successful introduction of hybrid wind systems into Chile. Initial cost will affect the benefit/cost ratio as well as limit the total number of systems which can be subsidized. O&M costs will determine the attractiveness of these systems to the Chilean implementing entities as well as the regional planning officials. Maintenance costs and fuel consumption for these pilot projects were minimized to practical limits (a requirement imposed by Frontel) at the expense of installing "oversized" wind systems (at least for the current village loads). If the systems are downsized while utilization is improved, the quality of service (as related to availability) can remain high. As discussed earlier, one way of improving utilization is to schedule more battery equalizations with the wind turbine. Productive and commercial uses of electricity such as pumping water, making ice, powering tools, and charging batteries for people in surrounding areas not only improve system utilization and profitability, but could also improve village welfare and income.

System downsizing also touches on two other load issues. First, there is the question: to which load should the system be sized? For these projects, long-term load growth was considered. Several new strategies to deal with the load growth issue will be proposed. They include designing the system based on fixed-term (perhaps two-year) load steps and building in the option of increasing system size as the load increases. This strategy may involve rotating equipment between several communities at different stages along the electrification path. The second load issue regards availability of power. The people in our three pilot villages accept short term power outages, at least when the outage is limited to a few days. Social impact analyses have been planned which will help to determine how load losses can be factored into system sizing criteria.

Alignment between costs, both initial and O&M, and revenue generated by tariffs is another important factor for making the introduction of wind hybrid systems in Chile a success. The issue of raising tariffs above what grid-connected consumers pay for similar service is politically difficult. These hybrid systems cost less than the line extensions that would otherwise be required for the pilot sites. Consequently, charging the hybrid systems' end-users more for their service appears to them as a social inequity. For the time, our best strategy continues to be minimizing O&M costs by transferring more responsibilities to the local operator which lengthens the periods between expensive visits to the sites.

The final two challenges of providing timely technical assistance and getting the most local participation possible are related. Certainly it is time-consuming and often difficult to respond to needs in Chile from the United States. It is, therefore, crucial that local people be trained to operate, maintain, and repair the systems. And while much training has already taken place, it is evident that much more must be done. Similarly, while there is a large spare part inventory at Frontel's Temuco office, this inventory should be expanded to include all US-sourced equipment, particularly the inverters and wind turbine controllers. Although such an inventory represents a relatively large expense, it is certainly justified for the pilot projects. As projects are replicated throughout Chile, the inventory will not represent such a high percentage of the total investment. Finally, it is worth mention that in-country "champions" or facilitators with a vested interest in the program are necessary. We were fortunate to have such persons in Chile who were able to deal with the political and business hurdles which almost always accompany the introduction of a new technology application.

FINAL REMARKS

The first six months of operation for the three pilot projects have helped to clarify the strengths and weaknesses in our wind hybrid program in southern Chile. The issues of system sizing, O&M, training, comparative economics, tariff design, and quality of service will be addressed in the next phase of the program, based on the experiences from this initial phase.

These early results are most important because new projects are being designed for Regions VIII and X. In fact, funding has already been approved for one pilot project on the Pacific coast of Region X at Bahía San Pedro. In the other regions interest is building. This solution for electrifying remote communities has been hailed by the local mayors, the CNE secretary, and the SAESA/Frontel management. Furthermore, it is the considered opinion of these authors that hybrid wind-energized mini-grids are economically competitive with grid extensions for a large number of communities in southern Chile.

While up to now the Chilean PER only recognizes 230 volt/50 Hz AC service, it is becoming clear that other types of service such as 12 volt DC for individual buildings may be allowed in the future. If so, this could open the possibility of adding battery charging stations to the applications suitable for wind hybrid systems in Chile.

ACKNOWLEDGEMENTS

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STANDARD METRICS AND METHODS FOR CONDUCTING AVIAN/WIND ENERGY INTERACTION STUDIES

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The awareness of the problem of avian fatalities at large scale wind energy developments first emerged in the late 1980's at the Altamont Pass Wind Resource Area (WRA) in Central California, U.S.A. Observations of dead raptors at the Altamont Pass WRA (Anderson and Estep 1988, Estep 1989) triggered concern on the part of regulatory agencies, environmental/conservation groups, resource agencies, and wind and electric utility industries. This led the California Energy Commission (CEC) staff, along with the planning departments of Alameda, Contra Costa, and Solano counties, to commission a study of bird mortality at the Altamont Pass WRA, California (Orloff and Flannery 1992).

In addition to the Altamont Pass WRA, other studies and observations have established that windplants kill birds. Depending upon the specific factors, this may or may not be a serious problem. Although many bird species are affected, raptors have received the most attention (Anderson and Estep 1988, Estep 1989, Howell and Noone 1992, Orloff and Flannery 1992, Hunt 1994, Luke and Watts 1994, Martí 1994, Howell 1995). The emphasis on raptors appears to be for several reasons: 1) eagles are afforded more protection under the federal Bald Eagle Protection Act than other federal and state protected migratory birds, and 2) raptors are symbolic megafauna and have greater emotional value than smaller species to many people. Raptor populations also tend to have smaller numbers of breeding adults and a lower tolerance for additive fatalities.

Other WRA studies have documented deaths of songbirds (Orloff and Flannery 1992, Pearson 1992, Winkelmann 1994, Higgins et al. 1995), water birds (Pearson 1992, Winkelmann 1994), and bats (Higgins et al. 1995). Generally, these have been common species in those areas, not subject to the degree of concern associated with raptor fatalities.

The current level of scrutiny and caution exhibited during the permitting of a new windplant development in the United States results in costly delays and studies. This is occurring during a highly competitive period for electrical production companies in the United States of America. Clarification of the bird fatality issue is needed to bring it into perspective. This means standardizing metrics, defining terms, and recommending methods to be used in addressing or studying wind energy/bird interactions.

COORDINATION

In 1992, CEC staff and the Pacific Gas and Electric Company sponsored a workshop that brought the wind energy and avian stakeholder groups together to discuss the issue and approaches to address it. This was the initial step in the development of a nationwide approach.

Other activities included the initiation of a research program directed by a wind energy company, which focused on the sensory and behavioral aspects of avian interactions with wind energy facilities. At about the same time, the National Wind Coordinating Committee (NWCC) was being formed to address all of the issues affecting the development of wind energy in the United States.

In July 1994, a larger national workshop was held, sponsored by the National Renewable Energy Laboratory (NREL), the U.S. Department of Energy, the American Wind Energy Association, the National Audubon Society, the Electric Power Research Institute, and the Union of Concerned Scientists. That workshop attempted to bring together all of the threads of information and concern about the issue. One major focus was to systematize the search for the factors responsible for avian deaths from wind energy facilities, and to place efforts to reduce fatalities on a firm, scientific basis. A dialogue between the regulators and other interest groups and the ornithological research community was needed to focus research on the questions that had to be answered to site facilities responsibly, and reduce fatalities at existing facilities. Ornithologists, bio-statisticians, and risk scientists were brought into the discussion at the July workshop.

Shortly afterward, the NWCC's Avian Subcommittee was formed to carry on the work begun at the workshop of identifying and setting priorities for wind energy/avian interaction studies and other activities addressing the issue. The Subcommittee has provided advice to funding agencies, facilitated the development of standard protocols for conducting wind energy/avian interaction studies, as reported in this paper, and promoted communications among participants in wind energy developments regarding approaches to resolve the issue.

In September 1995, the Avian Subcommittee and NREL sponsored a second national workshop in Palm Springs, California near a major wind energy development area, to facilitate communications between avian researchers and a diverse stakeholder group. The meeting produced a recommendation that a group of ornithologists, statisticians, and environmental risk specialists develop a set of standard metrics and methods for studying wind energy/avian interactions. This product would describe standard measurements, concepts, and methods and allow studies in different areas to be compared, making it easier to identify causal factors in wind energy/avian interactions.

The momentum for this document was carried on by NREL and the Avian Subcommittee. NREL personnel developed strategy for making this document a reality. They also selected a writing team and a review team composed of members of the main stakeholder groups. The writing team met and drafted an outline, which was subjected to a stakeholder and peer review. This document will be complete in late fall of 1997.

Guidelines Writing Team

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METRIC AND METHODS

All stakeholders decided it was important to set clear study objectives, use sound scientific sampling protocols, and employ standard and widely accepted field measurement methods. These repeatable methods would require the flexibility to accommodate varying research objectives while resulting in data that can be compared and pooled from multiple research efforts throughout the nation and world. The following describes the framework of metrics, methods, and concepts endorsed by the stakeholders. Over time, the cumulative results will become increasingly beneficial.

Objectives

The objectives of standard metrics and methods are:

1. To promote the use of sound scientific principles in the collection of data necessary for the responsible permitting and development of windplants.
2. To provide a reference for use by all stakeholders in assembling an adequate body of information to:
 - a. assess the effects of a windplant project on all bird resources.
 - b. aid in assessing the suitability of a proposed windplant.
3. To provide sufficiently detailed and clearly understandable methods, metrics, and definitions for use in the study of wind energy/bird interactions.
4. To promote efficient, consistent, cost effective methods which will produce comparable data and reduce overall need for some future studies.

Research studies can be divided into level 1 (general) and level 2 (focused special studies). This paper will focus on a discussion of level 1 studies. The methods, measurements, and relationships (metrics) considered level 1 studies are a product of review and consensus by scientists representing multiple stakeholders including: university researchers, agency professionals, utility representatives, environmental groups, and the wind industry. Although each component of the Methodology and Measurements seems simple and straight forward, the details and execution of each is complex. All of

these methods, measurements and concepts will be addressed in greater detail in the Guidelines document being prepared by the Avian Subcommittee of the National Wind Coordinating Committee.

Methodology and Measurements

Bird Utilization Counts - These are conducted to document bird use at study sites. They are conducted in repeatable ways using standard methods, so that results can be compared with bird utilization counts from other studies. The Bird Utilization Counts are conducted during defined time periods and during appropriate seasons to document behavior and relative abundance of birds using the area. While turbine and wind noise can mask bird calls, there are cases where the use of bird calls may be desirable. In Before-After-Control-Impact (BACI) methodology, the use of bird calls for measuring utilization levels could result in unacceptable bias for the Before and Control locations when compared to the added noise of operating wind turbines in the After and Impact areas. Each situation must be considered specifically with appropriate and supportable decisions made. This will insure that turbine noise will not bias Bird Utilization Counts and subsequent Bird Utilization Rates. We suggest recording all birds detected by sight and sound and documenting the method of detection (e.g., sight, sound, both). The method of detection can be considered during data analysis. Situations with many birds and few birds may require modification to Bird Utilization count methods. Variable and fixed plot surveys may be selected to accommodate the situation. In either case, the distance from the observer to each bird should be estimated and documented. In situations when birds are numerous, instantaneous counts could be made every one minute (or other time interval). The utilization count methodology is flexible and accommodating. Bird activities documented include: flying, perching, soaring, hunting, foraging, duration of time observed, and behavior close (≤ 50 m) to WRA structures. The height above ground and the horizontal or line of sight distance each bird is from the observer and wind turbine should be documented.

Bird Utilization Rate - Bird Utilization Rate is derived from the Bird Utilization Counts. The Bird Utilization Rate is the number of birds detected utilizing the area (e.g., a defined area such as 50m radius or per square meter) during the Bird Utilization Count time period. Rates can be developed for species, other taxonomic groups, all birds observed, average duration of bird presence in the area or cumulative bird minutes utilizing the area. These and other rates can be developed for specific covariates such as: natural communities, seasons, and distance from nearest turbine.

Example formulas for Bird Utilization Rates are:

$$\frac{\text{No. of birds observed}}{\text{Time or Time and area}} = \text{Bird Utilization Rate}$$

$$\frac{\text{Total minutes all birds observed}}{\text{No. of birds/time or /time and area}} = \text{Average Utilization Minutes}$$

$$\frac{\text{No. of birds observed}}{\text{Time/meter}^2} = \text{Bird Utilization Rate Per Square Meter}$$

Dead Bird Search - Dead Bird Searches are conducted in a defined area, which may include the complete project site or a sample of a larger project site. Complete coverage of the search area is important in detecting dead birds. The number of dead birds or dead bird parts found at each search site is documented. The search area may be circular, rectangular, or square, and be of

varying sizes. The methodology allows this flexibility. Search area can be discussed as fatalities per meter square or other size area, as long as the sample methodology has been documented adequately to make inter-study comparisons. Documented information may include: bird species, sex, and age, estimated time since death, cause of death, description of injury, vegetation series, distance to nearest turbine, distance to nearest structure, and distance to important habitat or topographic features. The information collected will allow a variety of analyses. Depending on study objectives, blind necropsies may be performed or required during this study phase.

Bird Mortality - Bird Mortality is the number of dead birds or dead bird parts documented per defined search area. The methodology allows for flexibility in creating bird mortality metrics. Documentation must be clearly set forth in order to allow comparisons to other rates created from the same methodology.

Example formulas for Bird Mortality are:

$$\frac{\text{No. of dead birds}}{\text{Defined search area}} = \text{Bird Mortality}$$

$$\frac{\text{No. of dead birds}}{\text{Meter}^2} = \text{Bird Mortality}$$

Bird Risk - Bird Risk establishes a relationship between bird utilization and bird deaths in an area. Bird Mortality is used as a numerator and the Bird Utilization Rate the denominator to develop a Bird Risk. The numbers of dead birds and bird utilization can increase proportionately without the risk changing. Bird risk can be used to compare risk differences for many variables, such as: near turbine areas and those at varying distances from developed WRA facilities; for species, other taxonomic groups, and all birds observed; for natural communities; seasons; turbine size; structure types; and other variables. Bird Risk can be used to compare risks between WRAs and with other types of facilities such as highways, power-lines, and television and radio transmitter towers. When well documented, many risks can be considered and will be comparable within and between studies. This flexibility allows these methods and metrics to serve the needs of many specific projects and situations.

Example formulas for Bird Risk are:

$$\frac{\text{No. of dead birds/ defined area}}{\text{No. of birds observed/time or time and area}} = \text{Bird Risk}$$

$$\frac{\text{No. of dead birds/meter}^2}{\text{No. of birds observed/time or time and defined area (m}^2\text{)}} = \text{Bird Risk}$$

$$\frac{\text{Bird Mortality}}{\text{Bird Utilization Rate}} = \text{Bird Risk}$$

Attributable Risk - The differences in Bird Risk may be used to discuss Attributable Risk. This is the risk that may be attributed to a specific location or situation, such as risk to the birds associated with the developed WRA vs. non-developed, nearby comparison areas or other possible comparisons. As the differences between risks increase, those locations and situations (relevant

variables) would be candidates for greater scrutiny and/or more focused studies. The ability to detect differences in risk is an important assumption in these methods and metrics.

Factors Influencing Bird Mortality Estimates

Carcass removal studies and Searcher Detection Efficiency Studies are conducted because Bird Mortality estimates can be affected by carcass removal rate differences and searcher detection differences. These studies and their results are important to conduct and document for each study to facilitate comparison between different studies. In studies with relatively few turbines, where all turbines are monitored, the level (rate) of carcass removal can assist in determining the frequency of dead bird searches needed to provide accurate dead bird number estimates. In studies with large numbers of turbines which can only be sampled, the level of carcass removal can assist in determining the accuracy of relative Bird Mortality numbers.

The Searcher Detection Efficiency Studies and resultant probability of detection (detection rate) are necessary in order to create factors that mathematically describe detection probabilities considering a number of co-variables involved in detection, such as: vegetation structure, vegetation color and density, searcher alertness (1st or 4th area searched in a day) or shadow effects (sunlight levels and angles) and possibly others. Some of these determinations are useful for creating factors for a specific study, and some are important for comparing the results to another study. Therefore, these studies and subsequent rates may provide valuable information for a particular study, for other study comparisons, or both.

Carcass Removal Study - In this study a known number of bird carcasses are placed at randomly chosen locations and monitored for removal by scavengers or by other means. Carcass removal activity can be quantified and calculated as a rate. This allows for comparison of carcass removal within WRAs or between different WRAs. If not detected, significant carcass removal rate differences would result in misleading Bird Mortality and subsequent Bird Risk.

Carcass Removal Rate - This is the rate at which bird carcasses are removed by scavengers or by other means. The results are used to adjust the number of dead birds detected.

A formula for the average time until carcass removal is:

$$\frac{\sum \text{Days for each carcass to be removed}}{\text{Number of carcasses}} = \text{Average time for removal}$$

Searcher Detection Efficiency Study - This is a designed study that includes placing a known number of dead birds or bird parts in a variety of locations with differing vegetative structure and color (green or brown). These searches take place throughout the day with differing sunlight angles (shadows) and differing observer alertness (1st, 2nd, 3rd search). Dead Bird Searches are then conducted and the results for each researcher are compared with the known number of dead birds. The detection success can be quantified and the probability of detection determined.

Searcher Detection Rate - This is a measure of the searchers detection probability in varying vegetative conditions, by time of day, and by 1st, 2nd, 3rd, etc. search of the day.

A formula for searcher detection rate is:

$$\frac{\text{No. of carcasses found}}{\text{No. of carcasses placed}} = \text{Searcher Detection Rate (P)}$$

Rotor Swept Area Metrics

Rotor Swept Hour and Rotor Swept Hour Risk - These measurements will look at bird use, mortality, and risk associated with different sized turbines. The rotor swept area has been treated in past instances as having a direct relationship with Bird Mortality. There is no data to support the notion that larger rotor swept areas along with other turbine characteristics may cause more or less fatalities with constant Bird Utilization Rates. Addressing this issue requires standardizing the measurements and relationship created so that the size differences can be isolated for the comparison. Rotor Swept Hour combines the size of the area swept by the rotor (rotor swept area) with the time it operates. Rotor swept hour risk will allow for comparison of risk associated with different rotor swept areas or turbine sizes in relation to the time they operate.

The formula for Rotor Swept Hour is:

$$\text{Rotor swept area (m}^2\text{) x hours of operation} = \text{Rotor Swept Hour}$$

This formula implies that a large turbine operating a low percentage of the time is comparable to a smaller turbine which operates a high percentage of the time. This may or may not be true. Whatever the case, differences in mortality, utilization and risk can be determined and normalized to compare the risk of each turbine.

Rotor Swept Hour Risk combines the rotor swept area, and time of operation (RSH), with risk to create Rotor Swept Hour Risk. The inverse of the dividend is used in order to more easily comprehend the comparisons between RSHR.

The formula for Rotor Swept Hour Risk is:

$$\text{Rotor Swept Hour Risk (RSHR)} = \frac{1}{\text{Rotor swept hour}} \times \text{Bird Risk}$$

In some instances, operation time may be considered as proprietary information and not available to researchers. In these cases, rotor swept area and rotor swept area risk may have to be substituted for RSHR. In other projects, an estimate of operation time may be developed from wind speed information and cut-in and cut-out specifications for the turbines in the study areas.

Other Studies

All Day Bird Activity Monitoring - This study documents day long bird activity during the various seasons. This information can be used to normalize Bird Utilization Rates for different time periods of the day or between different WRAs.

Specialty Studies - These are modeling or manipulative studies used to investigate specific questions. These are focused (level two) studies, usually conducted in response to findings of a more general (level 1) study. Examples of these types of studies are:

- Population Studies
- Risk Reduction Studies (reduce effects)

These studies are beyond the scope of the paper, and require additional metrics and methods.

CONCLUSIONS

The task of understanding and reducing avian fatalities due to interactions with wind turbines provides a good example of how science and policy can interact. The stakeholder groups that make up the National Wind Coordinating Committee, and its Avian Subcommittee, recognized that it was important to use credible science to produce good policy. They also recognized that all of the stakeholder groups have to be involved to establish scientific credibility. The Avian Subcommittee's work has helped to focus and standardize studies in a productive and cooperative manner.

The Subcommittee hopes that the methods and metrics developed and discussed in this paper will be reviewed and adapted for use by the ornithological community in all applied studies of bird interactions with wind turbines, and potentially other technologies. This should allow information to be pooled and compared between regions of the United States, and other countries around the world where wind energy development may occur. By doing this we can reduce the impacts on birds from existing facilities, and minimize impacts at new locations.

GUIDELINES DOCUMENT

The avian subcommittee of the National Wind Coordinating Committee has established a Guidelines Subcommittee to produce the guidelines document:

"Guidelines and Suggested Methods for Studying Wind Energy/Avian Interactions"

This document has been drafted and will be available in late fall of 1997. For information on availability please contact:

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**Overview of the
U.S. Department of Energy/National Renewable Energy Laboratory
Avian Research Program**

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ABSTRACT

As wind energy use continues to expand, concern over the possible impacts of wind farms on birds continues to be an issue. The concern includes two primary areas: the effect of avian mortality on bird populations, and possible litigation over the killing of even one bird if it is protected by the Migratory Bird Treaty Act or the Endangered Species Act or both. In order to address these concerns, the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL), working collaboratively with all stakeholders including utilities, environmental groups, consumer advocates, utility regulators, government officials, and the wind industry, has an active avian-wind power research program. DOE/NREL is conducting and sponsoring research with the expectation of developing solutions to reduce or avoid avian mortality due to wind energy development throughout the United States. This paper outlines the DOE/NREL approach and summarizes completed, current, and planned projects.

HISTORY OF DOE/NREL AVIAN-WIND POWER RESEARCH

Prior to 1992, no centralized, coordinated research program existed that examined the potential impacts of wind plants on birds. Most of the research effort in North America was being focused on the Altamont Wind Resource Area (WRA), primarily because of concern regarding the resident golden eagle (*Aquila chrysaetos*) population. Beginning in 1992, however, increasing concern from the public and conservation organizations regarding possible negative impacts of wind power caused the U.S. Department of Energy (DOE) to direct the National Renewable Energy Laboratory (NREL) to initiate a coordinated research effort. To initiate this research, NREL developed a three-pronged effort:

- Facilitate several ongoing research efforts, by providing expert guidance and funding. One such research project looked at the golden eagle population in the Altamont WRA.
- Help organize "The National Avian-Wind Power Planning Meeting," which was held in July 1994,¹ and involved stakeholders from DOE, American Wind Energy Association, National Audubon Society, Electric Power Research Institute, Union of Concerned Scientists, and other interested public and private parties. This meeting was the first time stakeholders had met with the goal of reaching consensus on ways to address avian issues pertaining to wind development.

- Develop a focused program of new research. This effort was guided by the research priorities established by stakeholders attending the second "National Avian-Wind Power Planning Meeting," held in September 1995,² and outlined in the next section.

PROGRAM APPROACH

With the support of DOE/NREL, the Avian Subcommittee of the National Wind Coordinating Committee hosted a meeting of government regulators, scientists, and other stakeholders in September 1995,³ to share ideas about research that could be helpful in predicting and reducing avian mortality resulting from wind turbines. Results of this meeting provided a prioritized list of research projects that represented a consensus among stakeholders. Priority projects included the following:

- Development of a conceptual framework of the principal causes of avian mortality at wind plants.
- Development of a common set of metrics for use in characterizing the potential or existing impact from a wind development.
- Continued development of research protocols and guidelines for data collection.
- Identification of appropriate study designs and statistical analyses.
- Application of new technologies, including the use of radar.
- Research of the cause of avian mortality in wind plants, including perching behavior.
- Testing the effectiveness of techniques designed to prevent birds from approaching or perching on turbines.

DOE/NREL have developed a research program that focuses on these priority projects. The initial set of research projects is designed to gain an understanding of the magnitude of the bird-wind power problem in a variety of geographic settings. Additional projects will then be developed that test ideas and hypotheses developed during the initial research projects and seek to reduce bird mortality in wind plants.

RESEARCH PHILOSOPHY

DOE/NREL have embarked on a research program that is based on careful consideration of stakeholder needs. To implement a project, the initial study plan must fully justify all sampling methods. This justification includes a review of the pertinent scientific literature and quantitative analyses of potential sample sizes (e.g., power analysis). As a standard, the research must produce results that are suitable for publication in peer-reviewed scientific journals. By holding to this standard, NREL ensures that stakeholders will receive recommendations that are based on rigorous research.

AVIAN RESEARCH PROJECTS

DOE/NREL's avian research program has resulted in a multifaceted approach to addressing the impacts of wind power development on birds. Each of the priority issues developed during the 1995 National Avian-Wind Power Planning Meeting are now being addressed and are outlined below. Table 1 summarizes those research projects currently under way. Table 2 summarizes research projects under negotiation.

Completed projects: The two National Avian-Wind Power Planning Meetings represent major advances in coordination among stakeholders and are largely responsible for the current cooperation evident in this area of research. Additionally, a white paper has been completed on the uses of population models and related methodologies in addressing wind power impacts.⁴ This paper develops broad guidelines for initial determination of likely influences of wind development on bird populations.

Projects nearing completion: The use of radar in examining the passage rate and heights of migrating birds was investigated at a proposed wind site in Montana by researchers at Montana State University. This research indicates that radar can be a valid approach in avian-wind research and will be particularly effective in evaluating nocturnal passages of birds.

Kenetech initiated research of the ecology of the golden eagle at their Altamont wind development. NREL assumed responsibility for the eagle research in 1994 and expanded the work to include development of models for predicting the viability of the population. This research is the first to attempt to develop population models of a bird population inhabiting a wind resource area. The results of this research will be available in fall 1997.

Kenetech had also funded laboratory research at Boise State University that was designed to determine the ability of birds to see, and ultimately avoid, turbine blades. DOE/NREL has now funded Boise researchers to complete data analyses of this laboratory work and publish the research results in scientific journals. These papers will include research results of the ability of birds to recognize different patterns painted on turbine blades. The first of several reports documenting the results of the data analyses will be available in late summer 1997. Field trials of the ability of birds to recognize and avoid blades may be conducted as a result of the laboratory research. The exact focus of any field work, however, has not yet been determined.

Another major recommendation of the second National Avian-Wind Power Planning meeting was development of a comprehensive document outlining preferred methods of study design, data collection, and analysis. To meet this goal, a team of scientists were gathered from the fields of avian ecology, research design, and statistics to write chapters for this document.⁵ This document will allow all stakeholders to refer to a single source for guidance on evaluating potential wind developments from site selection through postdevelopment monitoring; it will be available in fall 1997.

Planned and recently implemented projects: One research project recently begun will investigate the influence of tower type (tubular versus lattice) and size (old versus new generation) on bird use and mortality. Another project still under negotiation will investigate the behavior of birds flying near, and perching on, turbines and determine the relationship between flight behavior and perching, and bird mortality. A research project to evaluate how bird flight diverters, which are installed on guy wires of turbines, affect avian behavior, use, and mortality is also under negotiation.

DOE/NREL also expects to fund multiyear avian-wind farm interaction research projects. Using before-after-control impact studies, these research projects will be designed to perform before and after construction studies of avian species at a wind farm site and a reference site. Variables to be investigated include, but will not be limited to, utilization, mortality, species composition, avian behavior, prey base, habitat changes, and wind farm characteristics; necropsies will be performed to determine cause of death. Key species population surveys and population modeling analyses may also be included, if the initial research indicates that population effects are probable and can be measured.

In addition, expert advice on avian monitoring has recently been requested by two small proposed wind developments, one of which resulted from a utility green marketing program. It is anticipated that NREL will be involved in other such projects, providing expert advice on study designs and identification of key issues which should be considered.

CURRENT AND FUTURE PROGRAM FUNDING

The projects summarized in Table 1 cover from one to three phases, with a phase representing approximately one year of work. In total, these projects represent slightly more than \$1.5 million of avian-related research.

Projects under negotiation, summarized in Table 2, are also phased projects, each one to three years in length. A total of approximately \$400,000 is budgeted for these projects, although continued funding is contingent on research results as well as funding availability.

As originally designed, the avian-wind farm interaction studies were expected to be funded at \$300,000–\$400,000 per year, for up to three years. The DOE Wind Program will provide NREL with funding guidance on how to proceed with these research projects, given the current funding limitations. The DOE Wind Program's position is that, due to the downturn in domestic wind development as a result of the electric utility restructuring, an opportunity currently exists to properly examine the avian issues. The scope of these projects will be determined in the near future.

In addition to funding specific research projects, NREL has experts in the fields of biostatistics, population modeling, epidemiology/mortality, ornithology, and statistics who are under subcontract or have consulting agreements. These experts are used to provide input to the design of new projects, provide critical review of reports on the research, and as consultants to a variety of issues related to the avian research program. Funding to support these experts is approximately \$150,000 a year.

SUCCESS OF PROGRAM

Although the avian research program has only been in existence at DOE/NREL since 1994, a major success of the program is the collaborative approach to defining the projects. By including all the stakeholders, including utilities, environmental groups, consumer advocates, utility regulators, government officials, and the wind industry, what was once a very contentious group is now able to work together more effectively in developing a program to identify the problems and develop solutions to avian-wind turbine interactions.

Another measure of success is the number of projects completed and the number of projects under way. During the next six months, several projects are scheduled for completion. The success of the program will be further defined as the results of these research projects are circulated among the various stakeholder groups and we begin to get feedback.

By next spring, DOE/NREL, working in concert with the Avian Subcommittee of the National Wind Coordinating Committee, will identify additional research projects to test ideas and hypotheses developed during the initial research projects, with the ultimate goal of reducing bird mortality in wind plants.

TABLE 1
CURRENT AVIAN RESEARCH PROJECTS

Project Title	P. I.*/ Organization	Project Objective	Location	Start	End
Population Study of Golden Eagles in the Altamont Wind Resource Area ^{6,7}	G. Hunt/ University of California - Santa Cruz	Determine survival and reproductive rate of golden eagle population; collect data necessary to develop population model to predict trend in survival of population	Altamont WRA, California	1994	1997
Avian Use of Norris Hill Wind Resource Area (pre-construction survey) ⁸	A. Harmata/ Montana State University	Establish WRA baseline avian utilization and mortality; determine # of swans, water fowl, neotropical migrants and resident raptors using the area; evaluate usefulness of radar in identifying bird migrations	Norris Hill WRA, Montana	1995	1997
Potential Impacts of an Operating Wind Turbine on the Flight Behavior of Migrating and Breeding Birds at the Green Mountain Power Searsburg Wind Turbine Project	P. Kerlinger/ Vermont Department of Public Service	Investigate the impacts of wind turbines on migrating birds during both pre- and post-construction periods in eastern North America	Green Mountain, Vermont	1996	1998
Wind/Avian Mortality Research and Model Development	R. Anderson/ California Energy Commission	Determine if the development and operation of a WRA would result in an increased risk of bird mortality	Tehachapi and San Geronio WRA, California	1997	1999
Raptor Visual Capacities and Blade-Pattern Conspicuity - Report of Studies Completed	H. McIsaac/ Boise State University	Analyze data collected over 2-1/2 years and write up results of those analyses	Boise, Idaho	1997	1998
Biostatistical and Population Modeling Analysis for Avian Wind Power Research ⁹	K. Pollock/ North Carolina State University	Development of a modeling framework for evaluating bird-wind power interactions	Raleigh, North Carolina	1996	1997
Comparing Differential Bird Risk Between Types: Tehachapi and San Geronio	M. D. Strickland/ Western EcoSystems Tech (WEST) & R. Anderson/ California Energy Commission	Compare bird use, behavior, and mortality at small and large turbines; compare tubular and lattice towers; develop recommendations for reducing bird mortality in wind farms.	Tehachapi and San Geronio WRA, California	1997	1998

* Principal Investigator

TABLE 2
AVIAN RESEARCH PROJECTS UNDER NEGOTIATION

Project Title	P. I.* / Organization	Project Objective	Location	Start	End
Effects of Bird Flight Diverters Installed on Guy Wires of Turbines	B. Wolff/ Conservation and Renewable Energy System (CARES) & M. D. Strickland/ Western EcoSystems Tech (WEST)	Evaluate the effects of bird flight diverters installed on guy wires of turbines on avian behavior, use and mortality	Klickitat County, Washington	1997	1999
Reducing Bird Perching and Mortality at the Altamont Wind Resource Area, California	H. McIsaac/ Boise State University	Determine the behavior of birds flying near, and perching on, turbines; determine the relationship between flight behavior and perching and bird mortality; explore factors responsible for bird-turbine interactions and bird deaths; develop recommendations for reducing bird-turbine interactions	Altamont WRA, California	1997	1999

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ASSESSING IMPACTS TO BIRDS FROM THE BUFFALO RIDGE, MINNESOTA WINDPLANT DEVELOPMENT

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INTRODUCTION

Northern States Power (NSP) plans development of a 425 MW windpowered electrical generation facility within the Buffalo Ridge Wind Resource Area (WRA) in southwestern Minnesota. In 1996, Western EcoSystems Technology (WEST, Inc.) was contracted by NSP to develop an avian monitoring protocol for the Buffalo Ridge windplant. This protocol (Strickland *et al.* 1996) was developed and peer-reviewed by numerous individuals representing the wind energy industry, U.S. Fish and Wildlife Service, Minnesota Department of Natural Resources, and conservation groups prior to finalization.

The WRA currently consists of three phases of development (Figure 1). Phase I, constructed by Kenetech in 1994, consists of 73 Model 33 M-VS turbines and related facilities, including distribution lines, meteorological towers, communication systems, transformers, substations, roads, and operations and maintenance facilities in the approximate center of the WRA, and generates 25 MW of electricity. Phase II, consisting of 143 turbines and related facilities sufficient to generate 100 MW of electricity, will be constructed by Zond Systems, Inc. beginning in the spring of 1997. Phase II will be located in the northwestern portion of the WRA. Phase III facilities capable of generating an additional 100 MW are planned for the southeast portion of the WRA. Plans call for the eventual production of 425 MW of electricity within the WRA. Studies were conducted in these three areas and a permanent reference area not scheduled for windpower development located along Buffalo Ridge northwest of the WRA in Brookings County, South Dakota.

The primary goals of monitoring windpower development at Buffalo Ridge are to evaluate risk to avian species from each phase of development and the cumulative risk to avian species from all windpower development in the WRA. The secondary goal of monitoring is to provide information that can be used to reduce risk to avian species from subsequent developments (Strickland *et al.* 1996). This paper describes the methods contained in the protocol and presents selected results of avian monitoring studies conducted by WEST in 1996. Most previous studies of windpower/avian interactions have emphasized assessing effects on raptors. Due to relatively low abundance of raptors on Buffalo Ridge, and based on conversations with Minnesota Department of Natural Resources personnel, this study emphasized assessing effects of windpower on passerines, waterbirds, and waterfowl. Details on the protocol and results of the first year studies are contained in Johnson *et al.* (1997).

METHODS

Experimental Design

The monitoring protocol follows a before/after and control/impact (BACI) design. The BACI design is a modification of a protocol proposed by Richard Anderson (California Energy Commission, personal communication) where avian use and mortality are measured on plots located at varying distances from turbines. Modifications to Anderson's protocol follow the sampling protocol A proposed by Manly *et al.* (1993), where use of sampling frames allow for mortality estimation for the entire windplant and reference areas and an estimation of use standardized by unit area and unit effort. Estimates of relative risk by species, attributable mortality due to the windplant, and other parameters are measured during this study. Data compatible with numerous other windpower projects in operation or under development are provided and risk is assessed based on a weight of evidence approach.

The BACI design combines collection of data before and after Phase II and III of windpower development with collection of data from the existing development and multiple control areas. A permanent reference area was selected that is as similar as possible, both physically and biologically, to the current and proposed windplant sites. Four areas are initially studied, the existing wind plant (Phase I) (denoted EW), the northwest development area (Phase II) (denoted NW), the southeast development area (Phase III) (denoted SE), and a permanent reference area (denoted REF). Data collected on the NW and SE sites will serve as reference data for the EW prior to development of the NW and SE sites and will also serve as pre-construction data for the future developments. As with the NW and SE sites, new sites monitored prior to development will act as references to developed sites. By sampling both reference and impact areas before and after windpower development, both temporal and spatial controls are used, optimizing impact assessment capabilities (Green 1979). By adding future sites within the Buffalo Ridge WRA to the monitoring effort, cumulative impacts of development are addressed. Analyses under the BACI design will be used for comparing the NW and SE site, as well as future developments, relative to the reference area(s) because one or more years of pre and post-construction data will be available.

The monitoring protocol is a product of interaction among scientists, industry representatives, the utility company, agency professionals and conservation groups concerned with potential effects of windpower development on wildlife in Minnesota. Monitoring activities combine relatively intensive surveys of species of primary concern (passerines and other non-raptor species) with relatively less intensive surveys of species of reduced concern (e.g., raptors and waterfowl). Passerines and shorebirds are of primary concern because of their abundance in the area and because of the presence of several species of concern (e.g., loggerhead shrike and Wilson's phalarope). Raptors, with the exception of the burrowing owl, are of reduced concern, primarily because the most common breeding species is the ubiquitous red-tailed hawk.

The weight of evidence approach is illustrated by the following discussion. Depending on the avian resource of concern, evaluation of effects from wind energy development include effects on individuals (e.g., reduction or increase in use of the area occupied by the turbines), and population effects such as mortality (e.g., death due to collision with a turbine). Several outcomes are possible from analyzing results of the avian studies. For example, a decline in avian use on the NW site after construction of turbines without a similar decline on the reference area(s) may be interpreted as evidence of an effect of windpower development on individual birds. The presence of more carcasses near turbines than in reference plots increases the weight of evidence that an effect can be attributed to windpower. A decline in use of both the reference and development area (i.e., an area with wind turbines) in the absence of large numbers of carcasses may be interpreted as a population response unrelated to windpower.

Passerine/Small Bird Surveys

Point count surveys within 100m (328 ft) radius sample plots are used to estimate relative density and use of all avian species on the study areas (Reynolds et al. 1980). We assume use is influenced by biological and physical characteristics of the site and/or the home range of the species. Each bird detected during counts is located in relation to existing or measured information regarding the physical and biological characteristics of the site.

A systematic sample of 21 turbine locations in the existing windplant and 40 proposed turbine locations in the NW site were selected as point count stations for measuring avian use. A systematic sample of additional points was selected from an area within 100m (328 ft) to 300m (984 ft) of public road rights-of-way; 11 within the EW, 31 in the NW area, 25 in the SE area, and 29 in the REF. The actual point count stations were offset from the road edge by a random distance between 100m (328 ft) and 300m (984 ft) perpendicular to the left or right of the road to allow for sampling road and non-road habitats.

Observations on each point are made once every two weeks from April 15 to November 15. Surveys are conducted between ½ hour before sunrise and 4 hours after sunrise. At each point, observers record all birds detected by sight or sound for a 5-minute period. Data recorded for each bird observation include time, species, number, estimated distance from the observer, activity, habitat, flight direction, and estimated flight height to the nearest meter. Weather data (temperature, wind speed and direction, cloud cover, precipitation) also are recorded each visit.

Raptor/Large Bird Surveys (RLB)

The objective of the RLB use surveys is to estimate spatial and temporal use by large bird species of interest on Buffalo Ridge and within each of the four study areas. Groups of birds recorded during RLB surveys include raptors, corvids (limited to crows), waterbirds (cormorants, pelicans, gulls, waders), waterfowl and shorebirds. Use is measured by making counts of birds observed within sample plots, and keeping track of the duration of time spent within the boundaries of the plot.

Six RLB observation stations are located within the NW site, SE site, and REF area using a systematic sampling procedure with a random starting point for the first location. When necessary we adjust location of the center of the point to the nearest location with an unobstructed view out to 0.8 km in at least 270°. Two observation stations are located within the EW.

Each RLB observation station consists of a 0.8-km (1/2 mile) radius circle centered on an observation point. Observations are made once every two weeks from April 15 to November 15. Observation times are rotated to cover all daylight hours. Each station is visited twice each sampling day, once during the morning (0800-1200) and once during the afternoon (1200-1600). Each station is surveyed about the same number of times during each period of the day each season. Data collected during each visit consist of continuous counts of bird use during a 30-minute and the location of first sighting and direction of travel is mapped. Broad categories of behavior (courtship, foraging, etc.) and flight patterns (perched, soaring, flapping, etc.) are recorded and flight height of each bird is estimated. Observations of flight pattern (including perching) and flight height are recorded when first observed and every 5 minutes of the survey.

PSB and RLB Risk Index

A relative index to risk (R) is calculated for all bird species observed in the NW, SE, and EW study areas by season using the following formula:

$$R = A * P_f * P_i$$

where A = mean abundance for species I adjusted for visibility bias, P_f = proportion of all observations of species I where activity is recorded as flying (an index to the approximate percentage of time species I spends flying during the daylight period), and P_h = proportion of all flight height observations of species I within the rotor-swept area of the turbines. P_h is calculated for two turbine types either in use or proposed for use on Buffalo Ridge. Turbine A is installed on top of a 36m (120 ft) tubular tower and has a blade diameter of 33m (108 ft). Maximum height of the wind turbine at the tip of the blade is 52.5m (174 ft). The rotor-swept area of Turbine A is 19.5m (64 ft) to 52.5m (172 ft) above ground. Turbine B is installed on top of a 50 m (164 ft) tubular tower. Two blade diameters are proposed for use, 46m (151 ft) and 48m (157.5 ft). Thus, the rotor-swept area of 26m (85 ft) to 74m (243 ft) above ground is used in all avian flight height analyses involving Turbine B because this area encompasses all rotor diameters.

Carcass Searches

Objectives of carcass searches are to (1) estimate the number of avian mortalities attributable to wind turbine collisions for the entire Buffalo Ridge WRA, and (2) relate the mortalities to the relative abundance of each species, and other parameters such as turbine characteristics and habitat. Mortality is measured by estimating number of avian carcasses in the windplant area whose death could be directly related to turbines. All carcasses located within areas surveyed, regardless of species, are recorded and a cause of death determined, if possible, based on field examination and necropsy results. Total number of avian carcasses is estimated by adjusting for "length of stay" (scavenging) and searcher efficiency bias.

Carcass searches are conducted at each of the 21 avian point count stations centered at a turbine within the EW and at each of the 40 avian point count stations centered at a proposed turbine location within the NW study site. Searches also are conducted at a systematic sample of 50% of the avian point count stations located within the 400m (1312 ft) buffer of roads (6 in EW, 16 in NW, 13 in SE and 14 in REF). Stations to be sampled for mortalities are flagged at the time of the first PSB survey. A 126m X 126m (1.59 ha) plot, centered around each turbine, ensures all areas within 63m (207 ft) of the turbine are searched. Transects are generally set at six meters apart in the area to be searched, and the searcher walks at a rate of approximately 30-45 meters (98-148 ft) a minute searching both sides out to three meters (9.8 ft) for casualties (Johnson *et al.* 1993). The number of transects and speed are adjusted by habitat type. On average, approximately 45 minutes are spent searching each plot. Searches of randomly selected turbines are conducted once every two weeks to locate and collect any mortalities found under turbines; however, casualties found at other times and places also are recorded.

Carcass removal studies are conducted in randomly selected carcass search areas at turbine locations and reference plots in all four study areas. Carcass removal trials are conducted within each of the following seasons: (1) spring migration (April 15 - May 15); (2) breeding season (May 16 - August 15); and (3) fall migration (August 16 - November 15). Trials are spread over most of the season to incorporate effects of varying weather, climatic conditions, and scavenger densities. Twenty carcass removal trials are conducted over the course of the study. Each trial consists of monitoring the fate of 15 birds of varying composition. Carcasses are selected to represent a variety of avian species and size classes. Carcass removal includes removal by predation or scavenging or removal by other means such as being plowed into a field.

We also estimate the percentage of avian mortalities found by searchers. Nineteen searcher efficiency trials are conducted in the carcass search areas. Searcher efficiency is estimated by season and major habitat (crop, CRP, noncrop habitats). Estimates of searcher efficiency are used to adjust the number of carcasses found, correcting for detectability bias. Carcasses used for searcher efficiency trials have the same composition as those used for predator removal trials.

Estimation of Total Number of Mortalities

The estimate of the total number of avian mortalities by species or groups of species is comprised of the three components discussed previously: 1) the estimate and associated variance for the number of carcasses detected per standardized search, 2) the estimate and associated variance for the mean length of time the carcass remains in the study area before it is removed by scavengers, and 3) the estimate and associated variance for the observer detectability rate.

The estimate of the density of carcasses in the study area, m , for the time frame between searches (14 days) is calculated by:

$$m = \frac{I * \bar{c}}{t * p}$$

where I is the interval between searches in days, c is the mean number of carcasses per turbine per search, t is the mean length of time the carcasses remains in the study area before it is removed, and p is the observer detectability rate.

The total number of carcasses are estimated using the following relationship:

$$M = T * N * m$$

where N is the total number of turbines, T is the number of 14-day intervals for extrapolating the estimate, and m is the estimated density of carcasses per turbine per search.

RESULTS AND DISCUSSION

A total of 158 species of birds was documented in the Buffalo Ridge study area from 15 April through 15 November 1996. Three species observed as incidental wildlife observations are listed as threatened or endangered by the State of Minnesota and/or FWS, including peregrine falcon (federal and state endangered), bald eagle (federal threatened) and loggerhead shrike (state threatened). All of these observations occurred during the spring migration.

A total of 121 species was documented during 4,312 observations totaling 12,819 bird sightings while conducting PSB surveys on all four study areas on Buffalo Ridge (Table 1). Avian diversity was highest in the spring (15 April - 15 May), followed by summer (16 May - 15 August) and fall (16 August - 15 November), whereas avian use was highest in the spring and lowest in the summer. The three most abundant bird groups during the spring period were blackbirds, sparrows, and waterfowl. In both summer and fall seasons, sparrows, blackbirds and swallows were the most numerous groups.

Thirty-five species were documented during 752 observations totaling 3,102 bird sightings while conducting RLB surveys in the Buffalo Ridge study area (Table 1). Both avian diversity and use were highest in the spring and lowest in the summer. The three most abundant bird groups on Buffalo Ridge during the spring were shorebirds, waterbirds, and waterfowl. In summer, the three most abundant groups were waterfowl, raptors and corvids, and by fall, the three most abundant groups were waterbirds, waterfowl, and corvids.

A total of 9,577 observations of birds flying were made during PSB surveys on Buffalo Ridge. Mean flight height was lowest for upland gamebirds (3.0m), swallows (7.5m), and woodpeckers (9.8m). Highest mean flight heights were recorded for waterbirds (50.2m), waterfowl (35.3m) and blackbirds

(24.0m). Flight height data from surveys were examined separately for the current turbines (Turbine A) and proposed turbines (Turbine B) on Buffalo Ridge due to different turbine heights. For Turbine A, 34% of these were flying within the rotor-swept area, whereas only 13% were observed flying within the rotor-swept area of Turbine B. Bird groups most often observed flying within the rotor-swept area were waterbirds, waterfowl, raptors, blackbirds, and shorebirds. There were no significant differences in flight height as a function of habitat or presence/absence of turbines.

A total of 2,734 flying birds was observed during RLB surveys on Buffalo Ridge. Mean flight height was highest for waterfowl (51.9m), followed by raptors (36.9m), waterbirds (36.8m), shorebirds (26.1m) and corvids (14.4m). Sixty-three percent of these were flying within the rotor-swept area of Turbine A, and 27% were within the rotor-swept area of Turbine B. Bird groups most often observed flying within the rotor-swept area during RLB surveys were waterfowl, shorebirds, waterbirds, and raptors.

Risk indices based on mean abundance adjusted for visibility bias, proportion of daily activity budget spent flying, and proportion of flight heights within the rotor-swept area of turbines were calculated for all species observed during surveys (Table 2). Based on this index for PSB survey data, species most likely to collide with turbines during spring, in order, are blackbirds, lapland longspur, and Canada goose. During summer, species most likely to collide with turbines are red-winged blackbird, common grackle and pectoral sandpiper. In fall, double-crested cormorant, lapland longspur, and sandhill crane.

Using data collected during RLB surveys, species most likely to collide with turbines in spring are mallard, black-bellied plover, and double-crested cormorant. During the summer season, mallard, pectoral sandpiper, and red-tailed hawk are most likely to collide with turbines. Species most likely to collide with turbines in fall are Franklin's gull, mallard, and ring-billed gull. This analysis does not account for differences among species in their ability to detect and avoid turbines, habitat selection, and other factors that may influence risk; therefore, actual risk may be higher or lower than indicated by this index.

Ten avian mortalities were found by WEST personnel in 1996 during 786 person-hours of searching, of which 220.5 person-hours were spent searching plots in association with turbines in the existing windplant. An additional two avian mortalities (mallard, unidentified grebe) were found by KWP maintenance personnel during the study period. Mortalities found by WEST on the reference area included a dickcissel that appeared to have been hit by a vehicle, and a rock dove that appeared to have been preyed upon. On the NW, one adult male blue-winged teal was found and evidence indicated the bird likely collided with a guy wire on a meteorological tower. The other mortality on the NW study area was a scavenged adult ring-necked pheasant found near a great horned owl nest in a grove of trees, suggesting cause of death was predation. Only one mortality was found in the SE study area, an intact chipping sparrow in a plowed field that appeared to have been hit by a farm implement. Five avian mortalities were found by WEST personnel within the existing windplant. Two of these (unidentified passerine feather spot and scavenged mallard) were found while conducting carcass searches at roadside survey points and did not appear to be associated with turbines or related facilities. The other three mortalities were found associated with turbines, including an immature barn swallow, an immature female dickcissel, and an adult Lincoln's sparrow. Field evidence and necropsy results indicated that these three birds died as a result of colliding with a turbine.

Based on number of turbine-related casualties found per search adjusted for searcher efficiency and scavenger removal rates, total avian mortality in the EW was estimated to be 100 during the 28-week period of study, or an estimated mortality rate of 1.4 birds per turbine during this period. A 90% confidence interval yields an estimate of total mortality of 3 to 216 birds within the EW during this time frame. This estimate is for small birds only, as no medium-sized or large carcasses were located by study personnel during standardized searches. No non-turbine related carcasses were found at turbine plots,

therefore no adjustments for background mortality were made. Locating a turbine-related carcass appears to be a rare event in this study area, emphasizing the need for several years of monitoring before accurate estimates of mortality for all size classes of birds can be made.

CONCLUSION

After reviewing results of the first year of monitoring under the new protocol, several conclusions may be made relating to results of this study. The REF area selected on Buffalo Ridge in South Dakota appears to provide a suitable reference, as habitat composition, avian abundance and avian diversity are similar to areas within the WRA in Minnesota. Based on data collected in 1996, avian mortality appears to be relatively low on Buffalo Ridge. Additional data on potential avian mortality in the WRA will be available following construction of turbines in the NW area and subsequent carcass searches on turbine plots. Overall results of the first year of monitoring indicate that the monitoring protocol used for this study is sufficient to provide data required to adequately evaluate effects of windpower development on the avian resource. Variability in data will be reduced with increased data collection over time, allowing for more accurate determinations of avian abundance, composition, habitat use, risk of turbine collisions, and mortality.

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TABLE 1. THREE MOST ABUNDANT BIRD SPECIES (BASED ON MEAN NUMBER PER SURVEY) OBSERVED DURING PSB SURVEYS AND RLB SURVEYS ON BUFFALO RIDGE, 15 APRIL TO 15 NOVEMBER 1996.

Spring Species #/Survey		Summer Species#/Survey		Fall Species#/Survey	
PSB Surveys					
Buffalo Ridge					
Red-winged Blackbird	2.35	Red-winged Blackbird	0.60	Lapland Longspur	1.59
Lapland Longspur	1.11	Barn Swallow	0.60	European Starling	0.56
Brown-headed Cowbird	0.40	Bobolink	0.35	Double-crested Cormorant	0.55
Existing Windplant					
Red-winged Blackbird	1.11	Red-winged Blackbird	0.49	European Starling	0.65
Canada Goose	0.55	Dickcissel	0.30	Red-winged Blackbird	0.55
Western Meadowlark	0.25	Sedge Wren	0.30	Barn Swallow	0.22
Northwest Site					
Red-winged Blackbird	3.26	Red-winged Blackbird	0.53	Lapland Longspur	1.15
Lapland Longspur	2.39	Bobolink	0.51	Double-crested Cormorant	0.97
Western Meadowlark	0.49	Barn Swallow	0.51	Barn Swallow	0.41
Southeast Site					
Red-winged Blackbird	1.46	Red-winged Blackbird	0.85	Lapland Longspur	5.89
Savannah Sparrow	0.54	Barn Swallow	0.51	European Starling	0.99
Western Meadowlark	0.42	Savannah Sparrow	0.37	Sandhill Crane	0.71
Reference Site					
Red-winged Blackbird	2.22	Red-winged Blackbird	0.67	European Starling	1.14
Brown-headed Cowbird	0.78	Barn Swallow	0.42	Lapland Longspur	0.61
Song Sparrow	0.40	Cliff Swallow	0.31	Barn Swallow	0.51
RLB Surveys					
Buffalo Ridge					
Franklin's Gull	0.80	Mallard	0.73	Franklin's Gull	2.52
Mixed Sandpiper	0.79	American Crow	0.35	American Crow	0.97
Mallard	0.73	Red-tailed Hawk	0.21	Double-crested Cormorant	0.91
Existing Windplant					
Mallard	1.75	American Crow	0.29	Double-crested Cormorant	1.13
Canada Goose	0.25	Mallard	0.21	Red-tailed Hawk	0.50
Gray Partridge	0.25	American Kestrel	0.18	Mallard	0.46
Northwest Site					
Mallard	1.29	Mallard	1.24	Ring-billed Gull	2.97
Greater Yellowlegs	0.42	American Crow	0.33	Mallard	2.14
Franklin's Gull	0.38	Canada Goose	0.24	Canada Goose	1.53
Southeast Site					
Black-bellied Plover	1.25	American White Pelican	0.33	Franklin's Gull	7.85
American Crow	0.38	Pectoral Sandpiper	0.33	American Crow	1.29
Red-tailed Hawk	0.25	American Crow	0.32	Snow Goose	1.07
Reference Site					
Mixed Sandpiper	2.63	American Crow	0.43	Double-crested Cormorant	2.38
Franklin's Gull	2.29	Mallard	0.23	American White Pelican	0.86
Double-crested Cormorant	0.54	Red-tailed Hawk	0.18	American Crow	0.73

TABLE 2. TEN SPECIES AT GREATEST RISK IN BUFFALO RIDGE WRA FROM PSB AND RLB SURVEY DATA BASED ON MEAN ABUNDANCE, PROPORTION OF ACTIVITY BUDGET SPENT FLYING, AND PROPORTION OF FLIGHT HEIGHTS WITHIN ROTOR-SWEPT AREA OF TURBINES.

Passerine/Small Bird Surveys		Raptor/Large Bird Surveys	
Species	Risk Index ^a	Species	Risk Index ^a
SPRING			
Red-winged Blackbird	0.834	Mallard	0.240
Unidentified Blackbird	0.395	Black-bellied Plover	0.235
Lapland Longspur	0.379	Double-crested Cormorant	0.153
Canada Goose	0.127	Red-tailed Hawk	0.088
Mallard	0.125	Greater Yellowlegs	0.087
Yellow-headed Blackbird	0.100	Franklin's Gull	0.078
Brown-headed Cowbird	0.097	Swainson's Hawk	0.072
Common Grackle	0.094	American Crow	0.044
Tree Swallow	0.067	Northern Pintail	0.026
Double-crested Cormorant	0.053	Canada Goose	0.023
SUMMER			
Red-winged Blackbird	0.205	Mallard	0.170
Common Grackle	0.065	Pectoral Sandpiper	0.072
Pectoral Sandpiper	0.052	Red-tailed Hawk	0.068
Cliff Swallow	0.045	American Crow	0.050
Mallard	0.038	American White Pelican	0.048
Brown-headed Cowbird	0.038	Swainson's Hawk	0.041
American Goldfinch	0.020	Canada Goose	0.033
Canada Goose	0.016	Black-bellied Plover	0.026
European Starling	0.013	Northern Harrier	0.013
Blue Jay	0.012	Wood Duck	0.010
FALL			
Double-crested Cormorant	0.557	Franklin's Gull	1.637
Lapland Longspur	0.519	Mallard	0.294
Sandhill Crane	0.143	Snow Goose	0.277
Unidentified Blackbird	0.122	Ring-billed Gull	0.260
Red-winged Blackbird	0.083	Double-crested Cormorant	0.245
European Starling	0.067	Canada Goose	0.235
Canada Goose	0.064	American Crow	0.167
Franklin's Gull	0.057	American White Pelican	0.110
Rock Dove	0.030	Red-tailed Hawk	0.108
Unidentified Sparrow	0.021	Sandhill Crane	0.084

^a Risk index calculated by multiplying mean abundance (#/survey) adjusted for viability bias times proportion of all observations where species *I* was observed flying times average proportion of all flying observations where species *I* was observed within the rotor-swept area of each of the turbines.

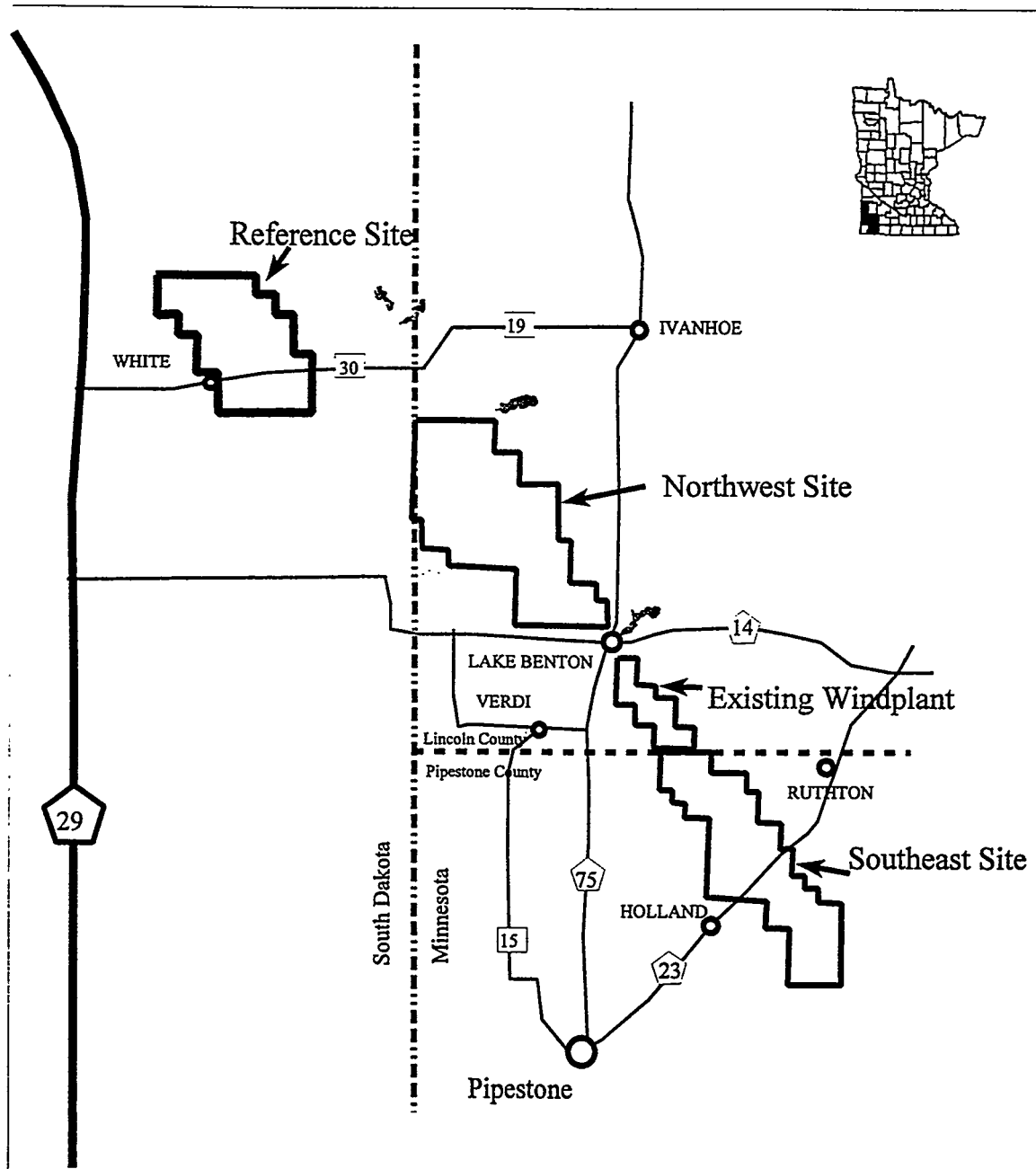


FIGURE 1. THE BUFFALO RIDGE WIND RESOURCE AREA (WRA) AND STUDY AREAS IN SOUTHWESTERN MINNESOTA

MODEL COUNTY ORDINANCE FOR WIND PROJECTS

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ABSTRACT

Permitting is a crucial step in the development cycle of a wind project and permits affect the timing, cost, location, feasibility, layout, and impacts of wind projects. Counties often have the lead responsibility for permitting yet few have appropriate siting regulations for wind projects. A model ordinance allows a county to quickly adopt appropriate permitting procedures. The model county wind ordinance developed for use by northwest states is generally applicable across the country and counties seeking to adopt siting or zoning regulations for wind will find it a good starting place. The model includes permitting procedures for wind measurement devices and two types of wind systems. Both discretionary and nondiscretionary standards apply to wind systems and a conditional use permit would be issued. The standards, criteria, conditions for approval, and process procedures are defined for each. Adaptation examples for the four northwest states are provided along with a model Wind Resource Overlay Zone.

INTRODUCTION

Good wind sites usually are located in rural areas which are under the jurisdiction of counties or the federal government. Wind projects on non-federal rural lands typically must obtain their primary siting permit from either the state or, when the state does not issue a permit, the county with jurisdiction over the site. In some states, the state issues permits for projects above a given megawatt (MW) size and the county may issue permits for smaller projects. The state may have a state-level environmental quality act which must be complied with and is implemented through either the state-level siting process or the local process. However, state environmental quality acts are of limited scope compared to the range of issues germane to a siting permit. State acts preempt county authority so a county typically implements the state law's requirements plus other local requirements in the permitting process. Even where the site is on federal lands, interagency coordination with counties is required and county requirements can be imposed on a project by the federal land management agency.

Counties have several roles which affect wind projects. First, counties in some states engage in land use planning which is formalized by a plan which prescribes what can be done where and under what conditions. Since land use plans anticipate and provide for future development, competing land uses are reviewed and resolved. The plan is translated into zoning and permitting ordinances. Second, even without a land use plan, county zoning ordinances often exist. In effect, zoning recognizes various classes of land uses including, for example, utility facilities (electric power plants), industrial areas, agricultural lands, parks, commercial and residential. Zoning ordinances say what land uses are allowed by right and which are allowed

conditionally. If a wind project is not allowed in a zone, a variance must be obtained in addition to meeting any permitting requirements that may be imposed.

Third, counties administer and enforce their land use ordinances. Since outright uses specified in the zoning ordinance are nondiscretionary, a county siting permit to develop such uses is not required. A land use or siting permit will be required when there are state or local discretionary criteria which must be met. Wind projects typically need to obtain conditional use permits which have discretionary and nondiscretionary criteria. Periodic review of land use plans or some permits is commonly done. Administration also includes processes for hearing permit modification and variance requests. Lastly, counties often administer other codes or rules which also require permits, e.g., electrical, mechanical, plumbing, overweight vehicles, waste disposal, and temporary sanitation.

County permitting processes typically address several objectives including:

- Ensure public safety. This applies to people associated with the project, neighbors and the public. Safety issues may arise from falling ice, catastrophic structural failure, derelict equipment, inappropriate access, or attractive nuisances.
- Identify and minimize on and off-site impacts. For example, potential biological/botanical, noise, erosion, noxious weed invasion, or neighboring property wind access impacts may exist. Projects may impact other on-site land uses, or historical, aesthetic, cultural, wildlife habitat, or archeological resources.
- Promote good land use practices. This may include minimizing impacts on adjacent properties with different land uses, maintaining compatibility with other on-site land uses, separating the facility from sensitive resources and incompatible nearby land uses, or use of on or off-site impacts mitigation.
- Express local preferences. This is done when the ordinance's procedural requirements or the criteria a project must meet are adopted. For example, one county may not care what tower types are used while another may require a given type. Another county may be sensitive to a certain problematic issue and impose additional criteria or process requirements. Some counties may see the absence of criteria or making wind an outright use as promoting economic development. Counties wishing to promote wind could do so just by establishing appropriate zoning and permitting processes in advance of development interest.
- Establish a venue to inform and involve the public. The public has a right to know what is proposed, what decisions are made and to inform those decisions with input. Public involvement is particularly important when discretionary criteria exist.
- Be legally defensible. The process and criteria must be properly implemented or the permit may be appealed and easily vacated. Good implementation reduces the likelihood of appeal.

These objectives need to be met in a reasonable manner and time frame, with some degree of flexibility, as much predictability and clarity as possible, and without imposing undue burdens on applicants.

THE NEED FOR A MODEL ORDINANCE

From the above it is apparent that county actions affect wind projects' timing, cost, location, feasibility, layout, and impacts. The county framework affects public perceptions of wind development in general and of particular projects. These factors and the necessity of a permit significantly affect project development risk.

California counties with over a decade of experience in San Geronimo, Tehachapi and the Altamont all have ordinances for wind projects and have been the primary permitting authorities. However, wind development has expanded nationally into counties without any previous experience or zones or ordinances appropriate to wind projects. Lack of appropriate ordinances significantly increases project permitting and development risks. Time to obtain a permit becomes very uncertain and public reactions to wind have not had a chance to form in the abstract and be codified.

Wind developers need to know as early as possible whether project development is likely feasible at a site and under what conditions. To the extent the issues and needs of the permitting process can be anticipated, the developer can assemble a permitting budget, tailor the public relations plan, design a project proposal which is permitable and make commitments regarding its on-line date.

The worst situation is when a project design is committed to and its on-line date set before the permitting procedures or siting criteria are known. When the county has not previously adopted appropriate siting regulations for wind the entire permitting process becomes open-ended. This adds time and significant risk to the development process and complicates the management of public relations. The county and developer are faced with the likelihood that the county's permitting criteria for wind will be decided within a context of public reactions to a particular company and project which also is the first in the county. Precedents are established which affect later projects. What may be appropriate standards for a particular project may not be an appropriate basis for all subsequent projects. The developer may be walking a fine line between advocating, with little flexibility, their proposed project and what are appropriate permitting regulations. Project opponents will exploit apparent conflicts of interest.

THE ROLE OF A MODEL ORDINANCE

Counties typically lack the resources and expertise to create new ordinances for wind projects, and to adopt them in advance of concrete need. Demands on county planning departments in other areas are so high relative to available resources that energy issues, much less wind, often get no attention until a specific need arises. If land use planning is being done and the county is aware of the location, quality and quantity of a potentially commercial natural resource, like wind, then that land use may be specifically planned for and the need to adopt appropriate ordinances will precede actual development proposals. Windy lands may be protected from competing incompatible uses. Other counties may adopt wind development as an economic development strategy and realize that appropriate ordinances facilitate wind project developments. Thus, it is in the wind industry's interest to advance the county's knowledge of its wind resources as that information becomes known.

Model ordinances and the ordinances of experienced counties often are turned to when a county wants to adopt new ordinances. A planner will review the documents and decide what issues are relevant and the best way to address them, and make a recommendation to the planning director, and a commission or board will make the

final adoption decisions. A model ordinance is an ideal starting place because it has been designed to be generally applicable, it covers the typical issues and addresses each in an appropriate and reasonable manner. Counties can adopt the model as a complete package or modify it as necessary to suit local conditions and preferences. Issues unique to the particular county are addressed at the time the model is adopted by the county.

A model ordinance will necessarily assume that the county already has the statutory authority to permit wind projects, exercises permitting responsibilities for other land uses, and would be the primary or lead permitting agency. A model also needs to be flexible enough to be adoptable, with minimal alteration, under various states' statutory authorities. If the county already exercises zoning authorities, a model overlay zone also can be adopted. An overlay zone is intended to apply along with existing zones, not to replace existing zoning.

THE NORTHWEST MODEL WIND ORDINANCE

In 1983 the Oregon Department of Energy (ODOE), with Coastal Energy Impact Program funding, published its first model county and city ordinances for wind development in Oregon. This project won a national award from the American Planning Association. The Bonneville Power Administration (BPA) subsequently funded ODOE to add model ordinances for transmission lines, and other small scale generating facilities. The full set was published in 1985. Since, wind development interest and plans expanded to other northwest states and considerable experience has been gained from wind developments elsewhere. Over time the complexion of some issues has changed as well as their importance, e.g., avian issues. Also, the technology has changed considerably although permitting authorities must be cognizant of the fact that permits may be sought for experimental, used and obsolete turbines of virtually any size and configuration.

For the above reasons BPA recently funded ODOE to update the model wind ordinance and to expand its applicability to the four northwest states (Oregon, Washington, Idaho and Montana). This effectively results in a model which is adoptable nationally because the four northwest states are so different. The model is generically written with regards to states' local government statutes so is necessarily adapted for each state it is used in. Adaptation instructions are provided for each northwest state which also serve as examples for other states. The model's text is italicized in brackets where typical variations exist which need to be adapted to state law. A separate model Wind Resource Overlay Zone accompanies the ordinance.

The model ordinance is published with its text on odd-numbered pages and explanatory commentary on even-numbered pages. The ordinance is a single chapter to simplify its integration with existing ordinances instead of requiring extensive and potentially redundant changes to many sections of previous ordinances. However, counties should amend existing zones and districts to identify those in which wind systems are permitted or prohibited and to cross-reference to applicable standards and procedures in the adopted model.

The optional Wind Resource Overlay Zone includes standards and procedures for applying the zone where wind resources exist. It promotes and helps structure assessment of wind and other resources in the zone. It encourages legislative as opposed to case-by-case review of wind projects in the zone. Research in an overlay zone and legislative decisions that follow from the results can expedite subsequent review of wind project applications in the zone. For instance, county awareness of

wind resources can justify the location and boundaries of the zone, and effectively prioritize land uses within the zone in a land use plan. An overlay zone focuses developers where projects are anticipated and their generic attributes have been reviewed. Initial reviews or inventories of sensitive habitats, species and plants may go hand-in-hand with establishment of an overlay zone. Where the wind resources exist over an area large enough to support multiple commercial projects an overlay zone is particularly important. If avian issues exist, the county can facilitate the efficient handling of them by picking and protecting from development a monitoring control site to serve all potential projects in the zone, and creating a standardized impacts monitoring and assessment program for the entire zone.

WIND FACILITY TYPES

The model ordinance proposes three types of wind energy facilities, each of which is subject to different standards and procedures. Facility types are necessary because wind projects on county lands can range greatly in scale, type and impacts. Counties may permit 100 MW projects on remote mountains or single small turbines associated with residences. The types are:

Wind Measurement Devices

Wind measurement devices consist of one or more devices to measure wind speed or direction and their associated supporting structures. The approval standards are non-discretionary. Towers up to 61 m (200 feet) are allowed with exceptions for taller towers. All towers must meet applicable state and federal aircraft safety requirements. The towers must be set back as required by the base zone, at least 3.7 m (12 feet) from buildings, rights-of-way and above-ground easements, and at least 6 m (20 feet) from turbine rotors.

Type I Wind Energy Conversion Systems (WECS)

This type includes up to two turbines on a given property. They are limited to 61 m (200 feet) maximum height. Setbacks of at least 5 rotor diameters are required from property lines. The turbine's furthest extension must be set back as required by the base zone and at least 3.7 m (12 feet) from buildings, rights-of-way and above-ground easements. The rotor must have at least 6 m (20 feet) clearance from an adjacent turbine's rotor, any current or foreseeable obstructions to its movement, and anywhere a person can stand. Turbines must be located to have minimal access to the winds.

Locational standards apply to Type I WECS. They are allowed in all districts and zones unless specifically prohibited but must comply with regulations for farm and forest zones and special districts. They are not allowed in protected areas, e.g., parks, wilderness areas, monuments, waysides, refuges, wildlife management areas, preserves, scenic or wild waterways and adjacent areas, wild fish streams and similar areas designated for protection by federal, state or local agencies. Where a land use plan designates unsuitable areas they are not allowed. An exception may be made if the project is an accessory use to a permitted activity, the project is specifically authorized by the controlling agency, the applicant provides equal or better replacement resources the controlling agency finds acceptable, or it is within the wind overlay zone.

Design criteria must be met. These include standards for foundations, geophysical and flood hazards, radio frequency interference, noise, dust control, access and

parking, public safety, and signs. Each of these standards has specific requirements. The noise standard uses both existing noise regulations and incorporates a relative noise standard. The foundation standard promotes minimum project footprint practices.

Applicable conditions of approval must be met. Potential conditions include requirements for interagency (federal or state) coordination, an erosion control plan, protecting discoveries during construction, a roadway repair fund, and a termination and reclamation plan with performance security. Enforcement procedures are specified and an enforcement deposit may be required. The project must comply with requirements of federal, state and local agencies and districts. The model endeavors to avoid the "chicken or egg" problem arising from other agencies' requirements by not dictating whether other agencies' requirements must first be satisfied. Rather the model requires the applicant to list applicable opinions, permits or approvals up front and allows the county application to be amended with other agencies' applications and decisions as they are made.

While the above may at first appear excessively burdensome on residential-scale turbine projects, the public safety requirements are easily met. Small turbines are not likely to be installed in sensitive areas and exceptions are provided. The design criteria are not dissimilar to what would be required of most improvements. The application of specific conditions of approval are up to the county which allows great flexibility as to which are needed for specific projects. When a WECS can not comply with the Type I requirements, it must be evaluated as a Type II WECS.

Type II WECS

The most complex type of WECS includes all other wind projects. These projects are subject to the locational standards, design criteria and conditions of approval described above, and to additional discretionary standards and policies. The additional standards include:

- **Setbacks.** The setbacks are differentiated on the basis of whether they abut non-residential or residential lots, or relative to dwellings. Dwelling setbacks may be mitigated by easements.
- **Wind Access.** Turbines must be located to have minimal access to the winds. This can be demonstrated by a wind access easement.
- **Visual Effects.** There are standards for setbacks from visual resources; for signs, lighting color, and marking; and to minimize impacts. An exception may be allowed when compliance adversely affects WECS layout or turbulence impacts.
- **Wildlife species and habitat.** Development and operation shall not have a significant adverse impact on species of concern or their critical habitats. This is a discretionary requirement.
- **Cumulative Impacts.** This standard addresses subjects not addressed by other standards, particularly off-site impacts. Road access, power lines, substations, adverse effects of design or operations, and impacts on wildlife access must be reviewed.

PROCEDURES

Since WECS involve discretionary standards and criteria, various procedures need to be defined. The model ordinance has procedures for:

- Pre-Application. These follow preexisting procedures.
- Application Contents. This defines what must be included for an application to be deemed complete. It ensures enough information is available to administer the criteria and standards of the ordinance.
- Public Notices. The process for a Type I WECS requires local notice and a 14 day comment period. A Type II WECS requires public notice and a public hearing.
- Appeals. When, where & by whom are defined.
- Duration of Decision. Defines how long the permit is in force.
- Permit Changes. Defines how changes are made, which require review and which do not.
- Periodic Review. Establishes a 5 year review cycle for review of conditions and enforcement deposit levels.
- Fees. Establishes fees.
- Advisory Committee Authorization. The county may establish one or more advisory committees to advise it regarding a Type II WECS application and periodic review. The makeup of the committee is defined.

Lastly, there are definitions in one section of the ordinance.

MODEL WIND RESOURCE OVERLAY ZONE

The Wind Resource Overlay Zone allows the county to identify where wind resources exist and to analyze the generic impacts of WECS on other resources or land uses in that area in advance of any particular permit application. This allows the county to make decisions about WECS proactively and in a legislative context rather than reactively in response to a specific application subject to quasi-judicial or administrative review. The model describes the mechanics of applying the Wind Resource Overlay Zone. A review process for a legislative amendment to the county land development or zoning code is provided. There are three standards for applying the overlay zone:

- A showing that the area contains significant wind resources.
- Identification of potentially conflicting resources in the area.
- Decisions are made to resolve conflicts. Guidelines are provided.

The model anticipates research will need to be done to support overlay zone decisions and provides for an advisory committee to be established. Guidelines for advisory committee research are given. A process for acting on the committee's report and the final decision are included.

CONCLUSIONS

County land use planning, zoning and permitting significantly affect wind project development. When counties are not prepared for development activities, they and permit applicants will be negatively affected. A model ordinance allows a county to quickly adopt appropriate permitting procedures. The model county wind ordinance developed for use by northwest states is generally applicable across the country and counties seeking to adopt siting or zoning regulations for wind will find it a good starting place. The model includes permitting procedures for wind measurement devices and two types of wind systems. Both discretionary and nondiscretionary standards apply to wind systems and a conditional use permit would be issued. The standards, criteria, conditions for approval, and process procedures are defined for each. In addition, adaptation examples for the four northwest states are provided along with a model Wind Resource Overlay Zone.

The Environmental Impacts of Windpower Development in Vermont: A Policy Analyses

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Introduction

A new century and a new chapter in wind energy beckons. Regulators, politicians, scientists and engineers will grapple with finding the proper combination of primary energy sources: a combination that will be sustainable, reasonable in cost, and the least offensive to both the environment and human perceptions.

Robert W. Righter¹

In the spring of 1996, construction of a six-megawatt wind power facility commenced on a mountain ridge in the town of Searsburgh in southern Vermont. While this process marked the beginning of physical development on the ridge, Green Mountain Power Corporation (GMP) had been planning the process for over 25 years. From wind speed data collection in 1971, to site selection, and environmental studies still ongoing, GMP has sought to increase their renewable energy portfolio by bringing wind power to the state of Vermont. While on the surface, wind power appears to be relatively pollution free, producing no emissions, it should be noted that there are environmental impacts associated with wind power and these would have to be addressed before any substantial development could occur. But how would this happen in Vermont? Power generating facilities are not subject to the Act 250 process²; rather they require certification from the Public Service Board (P.S.B.). As the project progressed, questions arose over just how the process would adequately address the environmental impacts associated with developing a remote ridge in southern Vermont.

Section 248 of Title 30 in the Vermont Statutes Annotated requires certification by the P.S.B. for all power generating facilities. While several sub-sections reveal similarities to Act 250, the process is procedurally different and as a result focuses on issues from an altered perspective. In preparing for and participating in the certification process, GMP identified several environmental impact issues in need of investigation. GMP initiated studies³ in several fields and hired consultants to investigate these issues with the hope that they would not serve as an impediment to their project. It is also necessary to note that GMP was working with a substantial grant from the Department of Energy and the National Renewable Energy Laboratory with the understanding that they would in turn provide information about the project for research and development in other regions. Preliminary analysis revealed the need for in-depth studies in four specific impact areas, including aesthetics, critical wildlife habitat, noise and avian studies. While

¹ Righter, Robert W. *Wind Energy in America: A History* Norman: University of Oklahoma Press, 1996, p. 296.

² Act 250 refers to sections of Title 10 of the Vermont Statutes addressing development in the state of Vermont. The act requires developers to obtain a landuse permit before construction and spells out the process for evaluating proposed developments.

³ While GMP initiated all of the studies, hiring different consultants in diverse fields (aesthetics, critical wildlife, noise, and avian studies), state agencies did contribute and oversee the process in most areas. Both the Public Service Department and the Agency of Natural Resources provided input and worked with the hired consultants in preparing and carrying out their studies.

some of these studies are still ongoing, the findings to date have revealed interesting results, none of which have provided evidence to halt the development.

However, comprehensive analysis of the process does unveil some important issues associated with the certification process and the development in Searsburgh. Specifically, concerns over the procedure of the certification process and its ability to adequately involve the public are noteworthy. In addition, some other concerns over the ability of the process to comprehensively address all of the environmental impact issues are apparent as inevitable comparisons are drawn to Act 250. While all participants in the process do not share the same concerns, different stakeholders have raised enough questions to justify a critical look at the certification process.

Statutory Process

Although commercial power generation development is not subject to the Act 250 process in Vermont, electricity is considered a public good, and thus development of any kind involving distribution of electricity is overseen by the P.S.B. Section 248 (a) (2) in 30 V.S.A. addresses this process: "Except for the replacement of existing facilities... (B) no such company may exercise the right of eminent domain in connection with site preparation for or construction of any such transmission or generation facility, unless the P.S.B. first finds that the same will promote the general good of the state and issues a certificate to that effect." In the case of wind power development in Searsburgh, GMP submitted a permit application for a certificate of public good in May of 1995.

Section 248 also addresses the criteria that must be considered by the P.S.B. in granting a certificate of public good. Under the second half of the section, the statutes list a number of considerations that the development must consider. Some of these include: not unduly interfering with orderly development of a region, meeting the needs of present and future demands for service in a cost effective manner, not affecting system stability and reliability, and providing an economic benefit to the state and region.⁴ In addition, this section also addresses environmental concerns, drawing direct ties to language used in Act 250. 30 V.S.A. § 248, subsection (b) (5) states "with respect to an in-state facility, will not have an undue adverse effect on esthetics, historic sites, air and water purity, the natural environment and the public health and safety, with due consideration having been given to the criteria specified in 10 V.S.A. § 1424a(d) and § 6086(a)(1) through (8) and (9)(K)." It is important to note here that while on the surface this section does not comprehensively address the various environmental concerns associated with a project such as the one proposed in Searsburgh, the references to 10 V.S.A. and the language in Act 250 are considered fairly comprehensive and for this reason are used as a direct reference. In other words, from the standpoint of addressing environmental impact issues, the criteria used for evaluating a permit application are akin to the Act 250 criteria.

In attempting to understand all of the aspects set out in 30 V.S.A. § 248, it is necessary to review the various references to the Act 250 statutes. 10 V.S.A. § 6086 addresses issuance of permits for development by the Environmental Board (E.B.). Within this section, the statutory language is similar to that mentioned above for the P.S.B. criteria. These include addressing issues such as air and water pollution, soil erosion, highway congestion, and municipal services, to name a few. Since these are directly referred to in 30 V.S.A. § 248, they must also be considered by the P.S.B. However, in addition to these aspects, the statutes also state the need to address scenic and natural beauty. 10 V.S.A. § 6086 (a) (8) states "will not have an undue adverse effect on the scenic or natural beauty of the area, aesthetics, historic sites or rare and irreplaceable natural areas."

⁴ 30 V.S.A. § 248 (b)(1) – (4).

In assessing how The E.B. and the P.S.B. utilize the above language, it is necessary to review the history of the language and the specific criteria set out in the Quechee analysis.⁵ Within this historic case, the E.B. clarified the language of criterion (8), stating "The term "undue" generally means that which is more than necessary—exceeding what is appropriate or normal. The word "adverse" means unfavorable, opposed, hostile. "Scenic and natural beauty" pertains to the pleasing qualities that emanate from nature and the Vermont landscape. In short, through criterion 8, the Legislature has directed that no project within our jurisdiction be approved if it has an unnecessary or inappropriate negative impact on the enjoyment of surrounding natural and scenic qualities."⁶ The Board went on to state that while this description was helpful in understanding the terminology of criterion 8, it did not identify any particular process appropriate for specific projects. In attempting to solve this dilemma, the E.B. created a more detailed process with the help of several specialists from within the state of Vermont.

Many have argued that the language of criterion (8) and the guidelines set out in the Quechee case are still too vague and not sufficient. However, they do represent progress in attempting to address these issues, and they do provide a process for both planning and evaluation. Furthermore, any type of wind power development would have to address these issues and pass the guidelines set out in the Quechee case. Just how effective this process is for wind power development will be addressed later in this paper, but it is these guidelines that set the context for the visual aspects of the project in Searsburgh.

Aesthetics

Far and away the most frequently cited environmental concern associated with wind power development involves the issue of aesthetics. Are wind turbines really as ugly as some would have us believe, or are they a beautiful example of modern technology? Clearly, the answer lies, to a certain extent, in the eye of the beholder. Unlike all of the other environmental impact concerns associated with wind turbines, aesthetics is the least quantifiable, as people's perceptions change with knowledge of the technology, location of facilities and many other variables.

An additional thought on the changing role of aesthetics in our society should be made in reference to technology. As our perceptions of aesthetic values associated with landscape change, confrontations with technology seem to increase as towns and cities are consistently faced with development issues involving new technologies. The wind power facility in Searsburgh can be seen as a good example of this. How we address these types of confrontations will be critical in the years to come as people begin to struggle with the dilemmas of technological improvements in our every day lives, and the often resulting loss of landscape. Robert Thayer targets this point when he states: "The American landscape simultaneously reflects our deep reverence for our natural context, our ingrained tendency to solve problems creatively to survive, as well as our discomfort with and apparent inability to tolerate living in a physical world comprised largely of the products of our own creation."⁷

In Searsburgh, GMP selected a remote site, which would have minimal visibility to the general public with the hope that they might better address the aesthetics concerns of the project by keeping the facility isolated.⁸ In addition to their remote siting, GMP also hired a consulting team to perform a visual analysis

⁵ While during the first 15 years of Act 250, criterion 8 was often mentioned only summarily, a case appealed to the Environmental Board in 1985 (*re Quechee Lakes Corp.*) presented an opportunity to definitively explain what the statutory language specifically refers to in using terms such as "undue adverse effect on scenic and natural beauty."

⁶ Environmental Board. In *Re Quechee Lakes Corp.* 3W0411-A-EB. 4 November, 1985.

⁷ Thayer, Robert L. *Gray World, Green Heart*. (New York, John Wiley and Sons, Inc., 1994), p. 32.

⁸ Whether or not this was the best approach from the perspective of researching public opinion to aesthetics issues surrounding wind power development in Vermont is not clear and will be discussed later in the paper. However, in interviewing those involved with the site planning process, it is clear that choosing a remote site, out of the public eye, was an integral component of the site selection process.

of the project to help describe the impact to both the public and the P.S.B.⁹ The scope of this visual study comprises five pieces, including a visual inventory, a survey of local residents perceptions, an on site visual analyses and recommendations to help mitigate negative visual impacts from the project.¹⁰

After the final analysis of the impact to the landscape was completed, it was set in terms of specific project characteristics and viewers' perceptions and attitudes about renewable energy sources such as wind power. This aspect differs from traditional visual analyses in that including viewer interpretations to the philosophy behind a type of development and how that might affect visual perceptions is not typical. In this case, the consultants explained the problem of trying to separate specific visual factors from viewer perceptions and attitudes of the rationale behind a given technology such as wind power. Various public acceptance studies indicate a higher acceptance level for wind power plants than other traditional power generating facilities specifically because of the association with clean energy.¹¹ However, while documenting acceptance levels of wind power technology within the study was practical, applying the results to traditional state standards was more difficult. Specifically, when using the State of Vermont E.B.'s standards for evaluating aesthetics, as outlined in the Quechee decision,¹² it is difficult to address visual impact without including public perception issues as mentioned above.¹³ This raises an interesting issue, which will be discussed further at length, later in this paper. However, in terms of the visual analysis, the consultants do state that the study attempts to balance equally both viewer perceptions of technology and the particular evaluation parameters set forth in the Quechee decision.

In using the Quechee analysis aesthetic evaluation process, one must determine whether a proposed project will create an adverse impact upon the scenic and natural beauty of the area. If this is found to be the case, then the impact must be evaluated as to whether or not it is "undue".¹⁴ In this case, when all the criteria of the evaluation were weighed collectively, it was determined that the project would have an adverse impact upon the scenic beauty of the area. However, in determining whether or not the impact would be undue, it was clear that the project did not meet the necessary criteria for designation as an undue impact. The criteria used in this second part include whether or not the project violates a clear, written community standard intended to preserve aesthetics, whether or not the project offends the sensibilities of the average person, and whether or not mitigating steps have been taken to improve the project's fit with it's surroundings. Since Searsburgh has no town plan, and GMP had taken steps to minimize the visual impact of the project, one could only question the criteria addressing offending the sensibilities of the average person. Once again, the difficulty of separating how people might view this new technology arose, and the conclusion was that average responses would probably be associated with interest and understanding of the rationale behind the project. As a result, the visual analysis concluded that while the project would create an adverse impact upon the scenic and natural beauty of the area, the impact would not be unduly adverse.¹⁵

In concluding the report, recommendations were made to help to further mitigate adverse visual impacts and to enhance the positive visual and perceptual elements of the project. Some of the recommendations included tower color and the amount of clearing around the towers, minimizing the visual impact of the substation and the entrance to the facility, as well as suggestions on vegetative screening in different areas. In addition, it was also recommended that the transmission line not run down Sleepy Hollow Road, (which

⁹ GMP hired two consulting firms to work together on the project. The Cavendish Partnership, Inc. of Cavendish, Vermont and T.J. Boyle and Associates of Burlington, Vermont prepared a visual analysis of the proposed project and submitted it to the P.S.B. on 3 August 1995.

¹⁰ Visual Analysis: GMP Wind Powered Electric Generation Facility. GMP Exhibit ___, TJB-1, p. 1. 3 August, 95

¹¹ See Appendix A

¹² It is important to note that the language in Title 30 VSA 248 (b)(5) expressly directs the reader to Act 250 guidelines and the Quechee analysis in Title 10 VSA 6086 (8).

¹³ Visual Analysis: GMP Wind Powered Electric Generation Facility. GMP Exhibit ___, TJB-1, p. 15. 3 August, 95

¹⁴ Title 10 V.S.A. § 6086 (8)

¹⁵ Visual Analysis: GMP Wind Powered Electric Generation Facility. GMP Exhibit ___, TJB-1, p. 19. 3 August, 95.

runs diagonally from Vermont Route 8 to Vermont Route 9) because it would disrupt the existing canopy of trees on that road. Instead, it was recommended that the line be set back from the road where it could not be viewed from Sleepy Hollow Road.¹⁶

Noise

One of the most frequently cited public concerns about wind power, after aesthetics, is noise. While significant technological improvements have been made in recent years, one can not argue that wind turbines are silent. They are not. All wind turbines create some audible noise, whether it is the “swishing” noise made by the blades as they pass by the tower, or a more mechanical noise in the turbine that gets carried with the wind. However, one aspect of addressing noise concerns that is not present in the aesthetics issue, is that noise can be measured. Analogies and comparisons can be drawn to other common noises in a development area, allowing for residents to know what to expect before the development is constructed.

In addressing the issue of noise in Searsburgh, GMP hired consultants to perform a noise impact analysis not only to study the impacts to surrounding human residences, but also to study the potential impact to critical wildlife habitat in the surrounding areas.¹⁷ In the report, descriptions of how noise is described as well as how it can be modeled are presented for the determination of what an acceptable level of noise would be. The findings were then placed in perspective with existing noise on the ridge so that conclusions could be drawn about specific noise impacts in different locations.

After background data had been compiled, turbine noise emissions for the turbine models were analyzed so that they could be compared to the background data.¹⁸ A computer-modeling program called “NTerrain” was utilized to predict noise levels at nearby receptors. The program considered factors such as vegetation and topographic barriers, and then produced expected levels for both critical wildlife habitat areas as well as residential receptor locations.¹⁹ When conclusions were drawn from the outcome, it became evident that noise levels from the turbines were expected to be well below the average background noise, with the exception of one house where at times it might be slightly audible, akin to a faint whisper.

Critical Wildlife

Issues surrounding critical wildlife habitat have not played as big a role in wind power development in other regions of the country as projects are typically located in broad open landscapes.²⁰ However, New England’s greatest wind sources tend to occur at elevation and for this reason usually present a different type of landscape than other regions. In Vermont, the Vermont Department of Fish and Wildlife (VDFW) has identified habitats that are typically critical to the survival of the state’s wildlife species. Given these designations and the landscape characteristics of the proposed site in Searsburgh, a study of critical

¹⁶ It should be noted that GMP did make this change in locating the transmission corridor, citing it as an example of taking mitigating steps (at greater expense) to improve the harmony of the project with it’s surroundings as set out in Quechee criteria.

¹⁷ Resource Systems Group, Inc. of White River Junction, Vermont was hired to perform the noise impact study which it completed on 26 July 1995. Resource Systems group, Inc. was chosen because of their expertise in evaluating noise impacts through a computer model they developed called “NTerrain.”

¹⁸ At the time of publication of the analysis, the specific turbine model was considered a prototype, and for this reason, the model name and specific noise emissions were not made public, but were provided to Resource Systems Group, Inc. for analysis.

¹⁹ All of the residences in close proximity to the facility are located to the west of the ridge. As the prevailing winds are from the west in this area, the concerns over noise impacts were further reduced as the frequency of winds carrying noise away from the residences increased.

²⁰ One exception to this statement is bird habitat, which has presented extensive impact problems at some facilities and is covered in a different section of this paper.

wildlife habitat and potential impacts was required.²¹

After extensive interpretation of VDFW and US Forest Service (USFS) data, and stereographic photographs taken of the surrounding area were interpreted, field investigations were performed in an attempt to accurately locate and evaluate critical habitats. Subsequently, it was determined that the only critical habitat found in the vicinity of the project was for black bears. Typical critical habitat for black bears occurs in three forms: mature stands of American beech trees, small forested wetlands, and travel corridors used for seasonal migrations between the former two habitat types and during the mating season. The study was then able to derive findings and conclusions specific to the project.²²

The issue of corridor crossings was the most difficult to address and involved several different processes. Three specific crossing areas were identified as probable for bear use. In an attempt to collect more detailed evidence, a barbed wire fence was erected over a ½ mile section at a continuous height of approximately 23 inches to try and snag bear hairs as the animals crossed over the wire.²³ During the first three months, six bear crossings were documented allowing for the conclusion that bears were using the corridor.²⁴ Over time, the fence length was increased and a second fence was added higher up, and closer to the project development site with the hope that bear movement might be tracked over the ridge, in-between the two clusters of wind turbines. While the study is still ongoing (a second round of crossing checks is scheduled to occur during the spring of 1997) the study was able to conclude that even if bear crossings were reduced at the corridor closest to the site, the other two crossings to the north and south would still be viable and useful.²⁵

In concluding the study, recommendations were made to help lessen potential impacts to black bear habitat and movement. Some of these included: reducing the amount of clearing on top of the ridge, thus minimizing the reduction of ground cover, minimizing the amount of clearing on the service road and then allowing it to brush in after construction, closing the access road to all non-service vehicles and performing all maintenance and inspections after 8 am to avoid early morning migration.²⁶ While the final interpretation of how the middle bear crossing will be affected by functioning wind turbines is still to be determined, it can be concluded that the overall impact to critical wildlife habitat would be minimal.

Avian Studies

Birds are impacted by wind power development in many ways, but no single aspect has received as much attention as collisions with turbines. This issue often elicits strong emotions from all concerned parties, and as a result grows in magnitude with each new project. However, research in the field has increased dramatically in the past 10 years, and several thorough studies have now been completed, shedding light on the specific areas of concern within the broader avian agenda.

²¹ GMP hired Jeff Wallin of Multiple Resource Management, Inc. in Leicester, VT to perform the critical wildlife habitat impact study. A report of the initial findings and progress was completed on July 31, 1995, with a follow up report scheduled for completion in 1997.

²² "Impacts to Critical Wildlife Habitats from a Proposed Wind Turbine Project." Jeff Wallin, GMP Exhibit ____, JW-1. July, 1995. p.6.

²³ This method of tracking bears created by Jeff Wallin is new and has not been used in other studies. However, in conjunction with VDFW, Jeff was able to prove that bears will not circumvent barbed wire, and if the wire is hung at average bear shoulder height of 23 inches, they will snag hair in crossing either over or under the wire.

²⁴ See Appendix B

²⁵ "Impacts to Critical Wildlife Habitats from a Proposed Wind Turbine Project." Jeff Wallin, GMP Exhibit ____, JW-1. July, 1995. p.8

²⁶ "Impacts to Critical Wildlife Habitats from a Proposed Wind Turbine Project." Jeff Wallin, GMP Exhibit ____, JW-1. July, 1995. p. 10.

Work on avian issues in Searsburgh started in June of 1994. At that time, a preliminary study was contracted in an attempt to illustrate what types, if any, of specific bird issues might arise at the project site.²⁷ It was determined that the study should cover three aspects of potential bird problems: impacts to breeding, migration, and winter nesting. After these preliminary studies had been performed, GMP next commissioned a more comprehensive analysis to assess the issues in greater detail and to interpret the earlier data, described above, within the specific context of wind power development. An important characteristic of the larger analysis is that it focuses on potential avian impact issues from a population perspective, not single bird mortalities. Three broad areas were considered: "the absolute and relative abundance of birds and types of birds present at the site during both breeding and migration seasons; the behavior of the birds in the wind turbine vicinity; and factors associated with the towers and habitat as attractions for birds."²⁸

In drawing conclusions for the studies, it was determined that the number of breeding birds in the vicinity was fairly typical of the concentrations in most Vermont forests and that no endangered or threatened species were observed. Thus, in regard to avian habitat and potential impacts, the study concluded that little impact was expected.²⁹

While avian studies are not complete in Searsburgh, as further studies are planned for the spring of 1997, the determination was made from the early studies and available research and data in the field, that avian impact issues as a result of the project would not be problematic. Simply put, the site in Searsburgh does not appear to present any of the critical impact issues experienced in the past at other facilities. Both the heavily forested landscape and the relatively typical southern Vermont topography combined for what appears to be a relatively safe location for wildlife near the wind power development.

Issues within the process

Clearly, in viewing the certification process as a whole, the issues surrounding aesthetics comprise the largest area for discussion. As mentioned above, no matter how much research, surveying and hypothesizing one does, personal opinions about aesthetics are often subjective, personal and very difficult to quantify. However, having said this, it is possible to identify areas of concern and I believe it is also important to consider some of the comments raised in regard to the earlier certification process.

The first area of concern associated with aesthetics issues must address the Quechee analysis. Questions are often raised in the Act 250 process about the ability of these guidelines to accurately address appropriate issues surrounding preservation of scenic and natural beauty. However, in evaluating the process in regards to a wind power facility, a more rudimentary question arises. Is the Quechee analysis appropriate in its design to even begin to address aesthetic concerns associated with power generating facilities? Several people think it is not because its design is geared towards commercial development such as additional condominiums in Quechee, Vt. They would argue that power-generating facilities are different by nature, and as a result can not be evaluated in the same way a residential housing development might be. However, before further discussion a closer look at the Quechee analysis is required.

Starting with the history behind the Quechee analysis, it is evident that in 1985 the E.B. sought more specific guidelines to be used in addressing development issues as they affected Vermont's rural landscape character. As mentioned earlier, after hearing testimony from several experts, the E.B. felt that a more definitive interpretation of the statutory terms such as "undue" and "adverse" could be produced. In

²⁷ David Capen and Daniel Coker from the University of Vermont were hired to perform a preliminary analysis of potential bird issues on the project ridge in Searsburgh. Their study occurred during June and July of 1994.

²⁸ "Avian Impacts Study for GMP Searsburgh Wind Turbine Project" Paul Kerlinger, GMP Exhibit ___, PK-2. 16 March 1995.p9.

²⁹ "Avian Impacts Study for GMP Searsburgh Wind Turbine Project" Paul Kerlinger, GMP Exhibit ___, PK-2. 16 March 1995.p. 10.

addressing how to define whether a project was adverse, the E.B. focused on how a proposed development might be compatible with the existing surroundings. Here, the Board presented several considerations for evaluation. The first centers around an analysis of the project's physical surroundings, focusing on land use, topography, existing development and scenic values. The second set of features includes questions associated with project design compatibility, including architecture, scale and density. The third set of considerations involves color schemes in relation to surrounding areas. The fourth set attempts to address issues of visibility, specifically where and how the location would be viewed. And finally, the fifth set of considerations addresses concerns about open space impact. Together these factors were all to be weighed collectively in deciding whether a project was in harmony with its proposed surroundings.³⁰

In using the above guidelines for consideration, the E.B. decided that if a proposed development should be found to present an adverse impact, then a second step would ensue to determine whether or not the adverse impact would be undue. Here, the E.B. raised three levels of concern in evaluating for an undue, adverse impact. The first section of the undue test applies to the planning process. Does the proposed project violate any clear, written community standard intended to preserve the aesthetics of the area?³¹ The second aspect to be considered has to do with how offensive the proposed project will be to the average person. If, in the E.B.'s opinion, a proposed project offends the sensibilities of the average person, or is viewed as "shocking" and "offensive" in relation to the existing landscape, then the project's impact will be considered undue. The final consideration involves the applicant in the process, and whether or not they have taken reasonable mitigating steps to improve the harmony of the project with its surroundings. Again, if the E.B. finds that this has not been done, then the project's impact would be viewed as undue.³² In meeting all three of these guidelines and the concerns associated with the project's "fit" with the areas existing landscape mentioned earlier, a project would then be viewed as acceptable.

Given these guidelines, concerns have been raised over how a power generating project, such as the one at Searsburgh, could be judged. Some of the people interviewed believe that the Quechee guidelines are clearly geared towards architecture and building developments. How could a coal or wood burning power generating plant fit in with its surroundings in Vermont unless it was in the middle of an industrial area in one of the state's two or three largest cities. In the case of wind power in Searsburgh, some would argue that it is a natural fit, since the ridge is windy and the development uses that resource. However, most others have countered that the development still presents large human-made objects in the middle of a forested, natural area, and could not possibly fit in with the surroundings. Given the contrast between how these contrasting opinions view the project, trying to evaluate what would "offend the sensibilities of the average person" is too difficult to do without taking one side's bias. Furthermore, one could also argue that this type of development would, by definition, be shocking and offensive to some, while others might be drawn more towards feeling it is an appropriate use of a resource with interesting technology.

Having presented the concerns with Quechee, it is not evident that those who express concern are opposed to the guidelines in their entirety, rather they feel that they are not able to adequately differentiate between diverse types of development. For example, where the guidelines address aspects such as scale and context and who will see the development and from where, one could not argue that these steps are inappropriate. Clearly they are helpful and do allow the evaluation to focus on key aspects. However, in its entirety, one could also not ignore the contrast between the guideline's applicability to residential development and commercial power development.

In the end, it is also important to remember that prior to the Quechee case, there were no specific guidelines for evaluation, and most people feel their introduction has been a step in the right direction. One should not

³⁰ Environmental Board in *re Quechee Lakes Corp.* p. 18. 3W0411-A-EB. 4 November 1985.

³¹ While there is some disagreement as to what exactly constitutes a clear, written community standard, most feel that a town plan or zoning ordinance would be appropriate examples.

³² Environmental Board in *re Quechee Lakes Corp.* p. 20. 3W0411-A-EB. 4 November 1985.

discount that in the absence of any other guidelines, these do provide a vehicle for evaluating different projects with some continuity, regardless of what kind of development is proposed. However, in looking for weaknesses, this aspect in the Quechee guidelines stands out in the minds of many participants and should be addressed in some form for future proposals.

In addition to the issues surrounding aesthetics, I believe another topic is worthy of discussion, as it was raised in several interviews. The degree to which the public has an opportunity to participate is also significantly different in P.S.B. processes than it is in the Act 250 process. Whereas the Act 250 permit process begins at the district level, certification for a power generation plant comes directly from the P.S.B. in Montpelier. This difference was the source of considerable frustration in the Searsburgh process and is deserving of further analysis.

Investigation of the statutes reveals that the P.S.B. is only required to hold one local meeting prior to the certification process occurring in Montpelier. 30 V.S.A. § 248 (a) (4) (A) states: "With respect to a facility located in the state, the P.S.B. shall hold a nontechnical public hearing on each petition for such finding and certificate in at least one county in which any portion of the construction of the facility is proposed to be located." The statutes then go on to say that all other meetings and technical hearings shall occur at locations that the P.S.B. selects.³³ Unlike Act 250 proceedings where district commissions hold all meetings within the district of the project, local residents and other interested parties are only given one opportunity to participate in a local meeting prior to P.S.B. certification.

In Searsburgh, this was a particularly sensitive subject, as many of the local property owners within the vicinity of the project live out of the state for a portion of the year and as a result were unable to make plans to travel to Vermont for a single meeting. Whereas we have discussed at length the areas where the P.S.B. certification process and the Act 250 process are similar in addressing impacts, this difference seems to stand out profoundly. Possible reasons for this difference are discussed later in the article, but it should not go without notice that local, public access to the process is not the same in these two processes. The drive from Searsburgh to Montpelier, where all of the other meetings and hearings were held, is over 100 miles, and the majority of the hearings were held during regular working hours. In order for interested citizens to attend, they would be forced to set aside full days, away from work, to travel several hours to Montpelier.

Another interesting aspect of the statutory regulations regarding the P.S.B. certification process has to do with notice. 30 V.S.A. § 248 (a) (4) (D) states: "Notice of the public hearing shall be published in a newspaper of general circulation in the county or counties in which the proposed facility will be located two weeks successively, the last publication to be at least 12 days before the day appointed for the hearing." In the Searsburgh case, notice for this and other relevant aspects of the process was placed in the Deerfield Valley News, which is a weekly paper covering the town of Searsburgh, and the Bennington Banner, a daily paper also covering the area surrounding Searsburgh. While on the surface this seems sufficient, and similar to the process generally followed for notification of public meetings, concerns continue in relation to the wind power project. When only one public hearing will be held locally, and the extent of the project is considerably larger than the kind of development one might expect in a remote location, questions have been raised as to why additional notice is not required. It has been suggested that notification should at least be sent by mail to adjoining landowners. While this could be considered above and beyond the scope of what is necessary to warn the public of a project, given the fact that only one hearing is required for a potentially large project, it is easy to understand why some feel more notification is necessary.

Having identified these areas of concern, it is also necessary to point out potential reasons for the differences between the Act 250 process and the P.S.B. certification process. While the scope of this paper,

³³ 30 V.S.A. § 248 (a) (4) (B)

and the general focus of concern in Searsburgh, has to do with environmental impacts, it should be noted that the P.S.B. is charged with a much larger task in performing its duties. Even if one were to center solely on their role in certifying a new power generating facility,³⁴ it becomes readily evident that abundant issues, aside from environmental impact, exist. To begin with, power generation facilities often require extensive analysis in areas such as electrical engineering, energy economics, transmission and distribution capabilities and local and regional demand, just to name a few. Unlike Act 250 projects, where the scope is often much more limited, evaluation of power generating facilities is incredibly complex, and as a result requires broad analysis in a number of areas. This is not meant to dismiss the relevancy of environmental impact issues in these types of projects, but rather to stress the necessity to put them in perspective with the greater number of considerations. Furthermore, of all the above mentioned issues requiring analysis, most are beyond the scope of the general public as they require specialized knowledge and training in the respective fields and are not appropriate for discussion at general hearings. For this reason, it is easy to understand why the statutes do not require the process to occur at the local level first, as it does with Act 250.

Overall, placing concerns about local participation is difficult at best. However, it should be noted by the P.S.B. and power developers, that local participation is integral, and should not be pushed aside in the interest of addressing more technical issues. Several studies in Europe have concluded that public participation is crucial to overall project success and should not be ignored. An example can be drawn from Paul Gipe's article on public input and aesthetics. He states: "In general, the prescriptions for optimizing aesthetic acceptance can be summarized by noting that designers, developers, and operators should make every effort to be good neighbors. Only when the wind industry places as much importance on being good neighbors as on aerodynamic efficiency will the public welcome wind turbines into their backyards."³⁵

Conclusion

In tying together all the pieces of how the certification process addresses potential environmental impact issues with wind power development, several aspects appear relevant. The process appears to meet most needs and as a result is viewed as sufficient by most people involved in the process. However, the concerns mentioned above are nevertheless significant and will continue to surface in future projects should they not be addressed. In looking specifically at the GMP project in Searsburgh, interviews have revealed that most interested parties feel that the environmental impact issues were addressed sufficiently, and that the concerns raised are minor in proportion to all the aspects of the project.

Is there room for improvement? In referencing the concerns spelled out above, one would have to say there is. Addressing issues such as aesthetics will never be easy, and there will always be critics when power-generating facilities are proposed. However, to the extent that the state of Vermont tries to address the related aesthetics issues, it is apparent that some aspects of a wind power development may not be adequately addressed by the Quechee analysis, which was originally developed from a condominium development proposal. Similarly, it is not evident how the issues surrounding public involvement should be addressed. But, clearly, several of the local citizens of Searsburgh feel due process and notice was not sufficient in this particular case. As wind power development grows nationally, addressing environmental impact issues will become increasingly important, and these two aspects in particular must be addressed.

³⁴ 30 V.S.A. § 203 addresses the duties of the P.S.B.. They include supervision of companies involved in gas and electricity generation and transmission, water distribution and sales, motor vehicle carriers, ferry transportation, telecommunications, and wastewater treatment. Given this diverse scope of coverage, it is easy for one to see the different levels of issues required for carrying out their duties.

³⁵ Gipe, Paul. "Design as if People Matter: Aesthetic Guidelines for the Wind industry." p. 4.

ECONOMICS OF WIND FARM LAYOUT

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ABSTRACT

The life cycle cost of energy (COE) is the primary determinant of the economic viability of a wind energy generation facility. The cost of wind turbines and associated hardware is counterbalanced by the energy which can be generated. This paper focuses on the turbine layout design process, considering the cost and energy capture implications of potential spacing options from the viewpoint of a practicing project designer. It is argued that lateral spacings in the range of 1.5 to 5 diameters are all potentially optimal, but only when matched to wind resource characteristics and machine design limits. The effect of wakes on energy capture is quantified while the effect on turbine life and maintenance cost is discussed qualitatively. Careful optimization can lower COE and project designers are encouraged to integrate the concepts in project designs.

INTRODUCTION

A brief survey of existing wind energy generation facilities would reveal a fairly wide range in machine spacing practice. Those in complex terrain tend to be relatively closely spaced within rows and have moderate to relatively large spacing between rows. Where the terrain is flat to undulating, arrays may have a larger spacing within each row and a smaller or similar spacing between rows. Questions arise whether these divergent layouts are optimized, and if not, then which type of spacing is to be preferred. It will be shown that the optimum spacing varies widely depending primarily on the wind resource characteristics and that a significant portion of the observed differences in machine spacing can be viewed as rational response on the part of designers to differing wind conditions.

As the wind industry matures and moves toward a competitive position on the open market, it has become imperative that designers and planners adopt methods which integrate the key concepts and data required to achieve optimized facilities. Aesthetics, environmental sensitivities, land owner preferences and commercial factors are each important criteria in layout design. This paper describes a method to determine the most preferable spacing, considering site-specific costs and energy capture potential. Once the preferred layout is established the economic effect of accommodating other criteria can be evaluated. Through the use of a simplified COE model, the sensitivity of the COE to variations in key input assumptions is explored. Then, by evaluating a range of spacing options, a configuration which minimizes the modeled COE is selected. The basic concepts and fundamental variables of this optimization are discussed. From an idealized base case, the optimization process is extended to add wind resource scenarios pertinent to more real-world situations. Some of the potential gains in cost effectiveness are identified and illustrated.

BASIC SITING CONCEPTS

As a wind turbine operates, a portion of the kinetic energy is extracted from the air flowing through the rotor disk and the air leaving the machine is reduced in velocity. Through natural mixing processes the kinetic energy in this "wake" zone is gradually replenished. Since the early 1980s the industry has gained significant experience with wakes and their effect on the energy production of downwind turbines. This phenomenon is well enough understood to make practical use of readily available wake models and wakes are now a significant factor in wind farm layout. The array efficiency of a layout expresses the true energy

output capability compared to a theoretical output with no wake impacts. A basic design goal then, is to maximize array efficiency through increased spacing. This goal is constrained to some extent by a decrease in the electrical system collection efficiency and/or an increase in the cost of additional infrastructure (road, cable, etc.) and the cost of developing larger land areas. However; these factors are generally overshadowed by the wind speed consideration to be outlined next.

A practical reality of large array design is that increased spacing translates into a reduction in the average wind resource for the project as a whole. Every project site has some degree of wind speed variability based either on topography or proximity to roughness elements. Ranking the potential machine locations in descending wind speed order produces a conceptual wind speed “gradient”. Small numbers of machines in locations without gradients form the exception but, in general, if one starts with the tightest spacing option and assumes that the first machine is placed in the very best location and each additional machine in the next best position, then any subsequent increase in spacing shifts all but the very best machine to increasingly less windy locations. Ignoring cost for a moment, if the wind speed gradient is sufficiently shallow and the array efficiency gains are sufficiently large then increased spacing results in a gain in net energy capture. At a certain spacing the net energy is maximized and wider spacing results in a loss in net energy capture because smaller array efficiency gains are more than offset by incremental reductions in collection system efficiency and reduced output due to the wind speed gradient effect. Adding the cost consideration back in has the effect of shifting the optimum spacing toward tighter options.

At many sites the wind gradient will fall and later rise with distance, i.e., after siting a portion of the desired project, the next best locations may be a large distance away. A full discussion of this topic is beyond the scope of this study, but briefly; there are two main options. Either continue with close spacing and accept lower output or skip to the better locations and add the connecting infrastructure to the “fixed” initial cost categories. The choice of which option to use would depend on wind gradient intensity, infrastructure costs, line losses, land availability, etc.

Wakes also affect turbine life and operations & maintenance (O&M) expenses, however, these effects are somewhat more challenging to quantify. The wake zone contains added turbulence which diminishes as a function of distance and ambient mixing rates just like the velocity deficit. The increased turbulence causes increased fatigue loading which results in shortened life for fatigue sensitive components, ultimately leading to a higher O&M cost. Often, some additional turbulence must be accepted as a practical necessity, just as we have come to accept a degree of energy loss due to wakes. Turbine designers should be aware that fatigue loading within an array will be higher than the ambient wind data indicates and array layout designers must consider the additional turbulence in relation to the machine’s design criteria when optimizing the layout. While a turbine designer may have the tools required to consider the cost implication of increased turbulence, a layout designer typically does not. Nor is it considered cost-effective to redesign the machine for each site. It is more practical to design machines to known loading criteria, for example the IEC Classification 1, and then ensure that site layouts, including wake-induced turbulence, conform to the design envelope of the selected machine. This procedure would lower the risks of unanticipated O&M costs and shortened machine life.

FIGURE OF MERIT - LIFE CYCLE COST OF ENERGY

The selected figure of merit for this study is a simplified life cycle design cost of energy (DCOE). The DCOE equation relates the sum of the annual operating cost plus a portion of the initial cost (numerator) to the annual energy production (denominator). This format provides a simple but objective way to evaluate the subject variables and illustrate the fundamental concepts.

$$\text{Design Cost of Energy} = \frac{(\text{Annual Operating Cost}) + (\text{Initial Cost} \times \text{Fixed Charge Rate})}{(\text{Annual Energy Production})}$$

The use of the DCOE model is not intended to produce accurate costing of energy or to analyze specifically how financing variables affect energy pricing, nor are there any provisions for the production tax credit.

Rather, the model is adopted as an efficient tool in comparing the relative cost of energy from different scenarios where cost and energy production are the primary variables.

MODEL INPUT ASSUMPTIONS

The change in DCOE over a wide range of spacing options utilizing both single and multiple row arrays is investigated for an 18 MW example project utilizing 36 machines with a 500 kW rating. It should be noted at the outset that the cases considered are idealized for the purpose of illustrating certain concepts. In an actual application, realistic values developed for the specific case at hand should be used.

The Initial Cost Factors are grouped into three main elements; the Machine Cost which includes the turbine and tower, the Balance of Plant which includes all civil, mechanical and electrical works, and the Development Cost which includes all project related activity leading up to construction. The intent is to represent the total cost related to establishing a fully commissioned facility. Only a few of these costs are sensitive to machine spacing but it is important to include an estimate of all costs so that the variables of particular interest are represented in the correct proportion to the whole.

TABLE 1 - INITIAL COST ASSUMPTIONS

Element	Cost (\$,000's)	Sensitive to Spacing ?	Proportion of Total Installed Cost
Machine	14,040 (390 per unit)	No	75.8 %
Balance of Plant			
Spacing Independent	3,300	No	17.8 %
Spacing Dependent	441	Yes	2.4 %
Development			
Spacing Independent	571	No	3.1 %
Spacing Dependent	164	Yes	0.9 %
Total	18,516 (1,028 per MW installed)	3.3%	

Table 1 shows the cost and proportionality of the major elements, considering those sensitive to spacing separately. The values presented are approximate and are based on experience in working on project development teams over the past twelve years. It should be noted that an analysis for other project sizes would show somewhat different proportions. Development costs, for example, are nearly constant over a range of project sizes and therefore become larger proportionately for small projects. The important aspect for the present study is that a very small percentage of the total cost is sensitive to spacing.

The Initial Cost Factors which are sensitive to spacing are scaled in the model as linear functions of length or area. A "primary length" is defined as the sum of the lengths of each row plus the sum of the distances between rows. The "primary area" is simply the geometric area for each machine times the number of machines, and in the case of single rows, a two diameter wide corridor is assumed. Table 2 shows the incremental scaling assumptions.

TABLE 2 - INCREMENTAL SCALING ASSUMPTIONS

Initial Cost :	Development	(Primarily land and permit)	\$370 / hectare	(\$150 / acre)
	Installation	(Primarily roads and cable)	\$100 / meter	(\$30 / foot)
Electrical Collection Efficiency :	Annual Loss		164 kWh / meter	(50 kWh / foot)

The Fixed Charge Rate (FCR) represents the annualized cost of financing, tax effects and other non-operating expense. For the purpose of this study the FCR is assumed to be 10.9%, as recommended by NREL² for design tradeoff analysis. In practice, the layout design team should use their in-house model(s) and assumptions.

Energy Production depends primarily on the machine power curve and the wind speed frequency distribution, and secondarily on the array efficiency, collection efficiency and machine availability. It is assumed that the machine power curve and availability are unaffected by spacing. Array efficiency depends heavily on machine spacing but even for a given spacing is sensitive to the aerodynamic characteristics of the machine and the mixing rate of the ambient flow. The widely used Park Model developed at Riso National Laboratory in Denmark is utilized here to generate predicted array efficiencies. The inputs (see Table 3) are the machine locations, the machine power curve, the machine thrust curve, the wind speed and direction distributions and the wake decay constant. The decay constant is thought of as a function of surface roughness and the selected value of 0.070 is consistent with a 0.025 m roughness length.

Operating Costs are represented in the model by three components as shown in Table 3. Maintenance is taken as a fixed cost scaled by the machine's rating plus a variable cost per kWh generated. Operating Expenses are assumed to be a percentage of the Initial Project Cost, and Land Costs are a percentage of gross revenue. It could be argued that maintenance is a function of spacing because increased distance will result in higher expenses, however the effect is minuscule. A more important question revolves around the wake-induced turbulence within the turbine layout and its effect on machine production, lifetime or maintenance costs. These impacts have not been included in the current cost model, but a qualitative discussion of relative turbulence estimates is included in the results section.

TABLE 3 - ENERGY PRODUCTION and OPERATING COST ASSUMPTIONS

Machine	40 m Diameter Pitch Regulated	Cp 0.41 from 3 to 12 m/s 500 kW rated output from 12 to 25 m/s
Base Case Wind Speed is a Rayleigh Distribution with an 8 m/s (17.9 mph) average.		
Availability		97%
Collection System Efficiency (substation and step-up transformers only)		97.6%
Land Cost		3% of Gross Revenue
Maintenance Cost		\$4 per Installed kW per Year + \$0.0025 per kWh Generated
Operating Expenses		2% of Initial Cost per Year

SENSITIVITY TO FACTORS CONSIDERED

Figure 1 illustrates an analysis of the sensitivity of the DCOE to various cost and energy production factors. From a base case of 36 machines in a single row with a 3 diameter (3D) spacing, the various factors are increased and decreased over a range of plus and minus 30% (multipliers of .7 to 1.3). This is a simple analysis and no attempt is made to quantify a probability range for each factor.

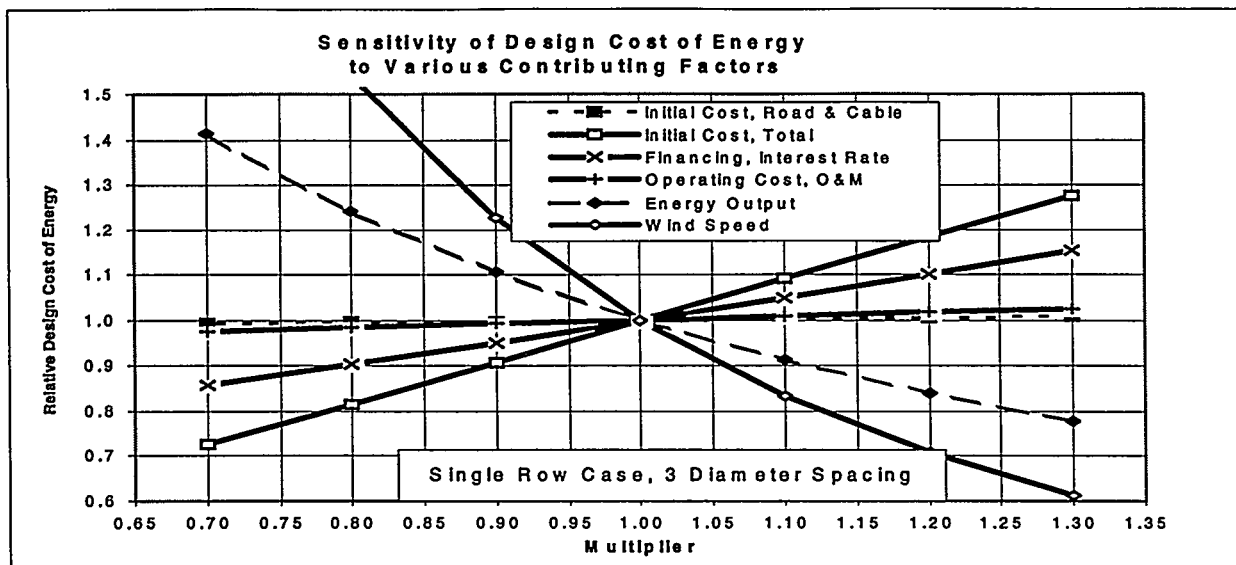


FIGURE 1 - SENSITIVITY ANALYSIS

After applying the Fixed Charge Rate, the numerator in the COE equation is composed of roughly 80% Initial Cost and 20% Operating Cost. Given that the initial cost of roads and cable is less than 3% of the total Initial Cost, significant increases in these costs have little impact on the DCOE. Likewise, proportional changes in the Maintenance Cost or the Development Cost (not displayed) have small effects on the DCOE. Variations in financing cost, modeled as a change in the equivalent interest rate of the FCR, produce larger responses in the DCOE and show about half of the influence of Initial Cost.

On the production side, the Energy Output has nearly a direct influence on DCOE, but Maintenance Cost is scaled by energy so the influence is slightly diminished. The change in energy for a given change in wind speed depends strongly on the average wind speed. In the range of speeds under consideration a squared function is approximately correct and it is assumed here for illustration. A 10% increase in wind speed will reduce the DCOE by about 17% whereas a 10% reduction in the total Initial Cost will reduce the DCOE by 9%. Since the cost factors which have been identified as variables of spacing are small compared to the whole, it can be expected that the interplay of factors affecting energy production will dominate spacing optimization.

RESULTS FOR A SINGLE ROW BASE CASE

The single row case illustrates the basic concept of the cost-performance trade-off and relates to practical applications, beyond small one-row clusters. Machines often are sited along exposed ridge features and the spacing choices are limited by the distance between ridges. Most often this results in large spaces between strings (rows) and the design problem is reduced to a series of single row optimizations. The base case considers a single row with idealized wind conditions of Isotropic Direction (all direction frequencies equal) and Uniform Speed (no change in wind speed across the project area). Figure 2 shows the Relative Initial Cost, Net Energy Production and DCOE for spacings ranging from 1.5D to 7.5D. From the figure it is seen that there is a high DCOE for tight spacing options. The key here is the large amount of time, based on the wind direction distribution, during which the machines are experiencing wake impact. The net energy initially improves dramatically as turbine spacing increases but eventually becomes asymptotic when wakes no longer effect generation. Before this happens the incremental costs and collection system losses outweigh the gains of wider spacing. Where the impact on DCOE of change in production equals the impact of rising project costs and losses, the DCOE minimum is achieved. In this idealized case, the minimum

occurs at about 4.5D with an array efficiency of 0.965. The result has limited applicability because in the real world wind directions are not isotropic and wind speeds are not uniform.

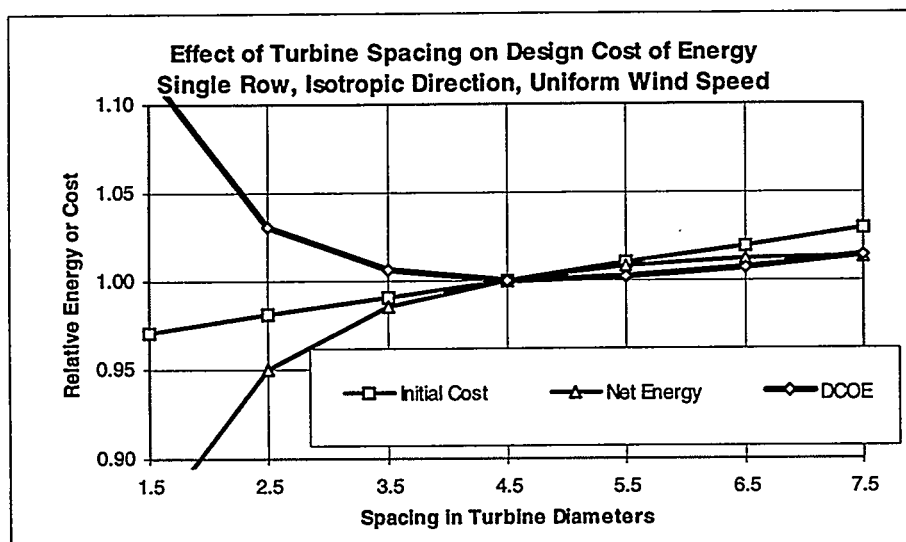


FIGURE 2 - IDEALIZED BASE CASE

WIND RESOURCE SCENARIOS

The effect of non-isotropic, non-uniform winds on spacing design is investigated by first considering two typical wind resource scenarios which are loosely correlated to the character of the surrounding terrain, and then independently changing the speed and direction variables to observe the sensitivities. Undulating terrain in more or less open country tends to have a “preferred” direction and a “moderate” wind speed gradient while complex terrain is more often associated with a “prevailing” direction character and “steep” wind speed gradients. The representative values selected for each scenario are given in Table 4. Wind direction is described by the annual frequency in each of eight direction sectors; two perpendicular to the rows in the layout, two parallel and four at oblique angles. Generally, the average wind speed in each sector also varies, with higher wind speeds being found in the prevailing or preferred directions, but for this study all sectors have the same average speed. The wind speed gradient is represented by a linear decrease in average energy output with increases in spacing. For example, in the moderate speed gradient case, changing from a 2D spacing to 3D would reduce the net output by 1.5%; changing again to 4D would further reduce the output to 3% less than the 2D output.

Referring now to Figure 3; in the Preferred Direction - Moderate Gradient scenario there is less wake interference than seen in the Isotropic case because the time in the affected sectors is less. Furthermore, the moderate speed gradient in this scenario imposes a penalty on the large spacing options, and from the slopes of the curves it can be inferred that this speed effect is more influential than the incremental cost factors which constrained the base case. The minimum DCOE is seen to occur between 2.5D and 3D. In the Prevailing Direction - Steep Speed Gradient scenario, there is a large penalty for accepting wide spacings due to the associated reduction in average wind resource. Although there are still large wake losses for the tight spacing options, the prevailing direction character allows the machines to be aligned in a direction which occurs infrequently. The net result is that relatively tight spacing will be more desirable when the non-prevailing directions are infrequent and the wind speed gradient is steep.

Figure 4 and Table 5 show additional results for other combinations of the wind resource variables. The uniform wind speed gradient case, for example, may be more relevant for small machine clusters. Due to their limited geographical extent they would often be considered to have less wind speed gradient than a large array in the same locale. The results indicate that small projects can be expected, in general, to have relatively larger optimum spacings even when the wind direction has a prevailing character.

TABLE 4 - WIND RESOURCE SCENARIOS

Direction Frequency :	Perpendicular	Parallel	Oblique
Isotropic	25%	25%	50%
Preferred	35%	15%	50%
Prevailing	60%	6%	34%
Speed Gradient :			
Uniform	0%	(Energy decrease per one diameter spacing increase)	
Moderate	1.5%		
Steep	4%		

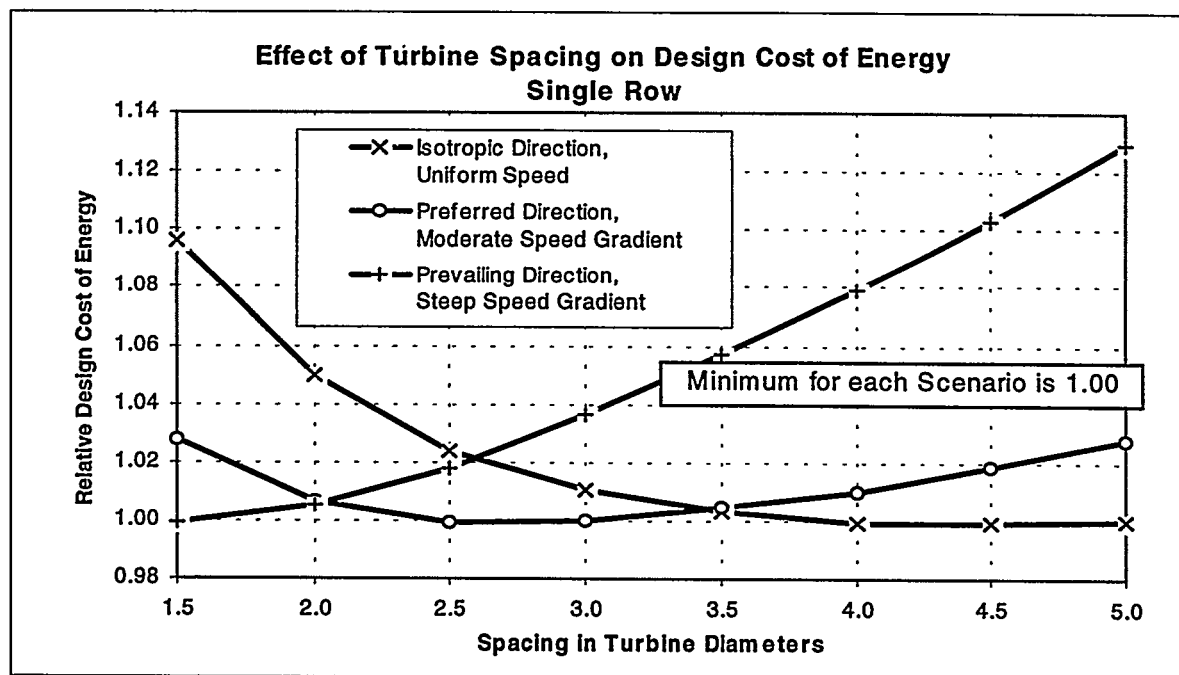


FIGURE 3 - SINGLE ROW ANALYSIS

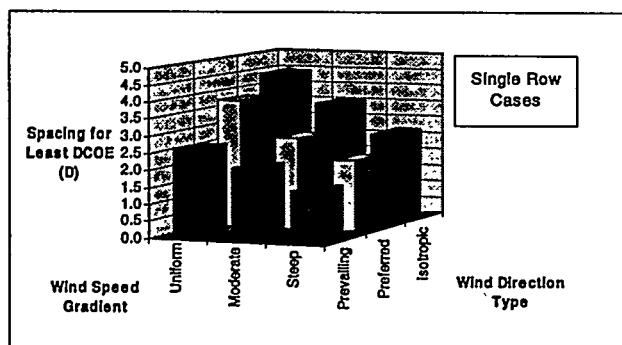


FIGURE 4 - SENSITIVITY TO WIND FACTORS
CONSIDERING THE WAKE INDUCED TURBULENCE

TABLE 5 - SENSITIVITY TO WIND FACTORS

Turbine Spacing for Least DCOE Single Row (Diameters)			
Wind Speed Gradient	Wind Direction Type		
	Uniform	Moderate	Steep
Isotropic	4.4	3.5	2.6
Preferred	3.9	2.7	2.1
Prevailing	2.6	2.1	1.5

Garrad Hassan and Partners have published a comprehensive study³ of loads modeling and verification including a section on wake-induced turbulence. The effect of wake-induced turbulence is expressed as an increase in design turbulence intensity (TI) required to meet the anticipated loads for the most affected machine in a five machine row. The required "worst case" Design TI is computed for a range of spacing options, over a range of wind speeds, for varying amounts of "in-line" running time and for several material properties (S/N curve slopes).

The above study's results, reinterpreted and extrapolated, have been plotted as the design turbulence intensity adder versus machine spacing for selected in-line sector frequencies. The values shown in Figure 3 are only appropriate for a very limited set of conditions, i.e. a component of a machine having an S/N curve slope of -8, designed to operate in a location with a 10 m/s annual average wind speed and an ambient characteristic turbulence (IEC) of 13%. Nevertheless, the "TI Adder" from the plot is used here to get an idea of the relative magnitude of the wake induced turbulence for the various spacings. The basic idea is that the induced turbulence is a function of both spacing and the time spent operating in the wake-affected sector. Operating at 2D for 10% of the time is about the same as operating at 4.5D for 20%.

Table 5 shows the values obtained from the plot for the selected single row spacing options and it is observed that the three TI Adders are in the range of 2 to 2.3%. Assuming, for the sake of argument, that these numbers have real meaning; then as long as the site ambient turbulence is less than 13.7% (IEC characteristic value) and the turbine is designed to meet the IEC Class B Turbulence of 16%, any of these spacing choices would be acceptable machine-site matches. In practice, this determination is very complex and the authors advocate a close working relationship between site designers and machine designers to ensure that machines are placed in environments for which they were designed.

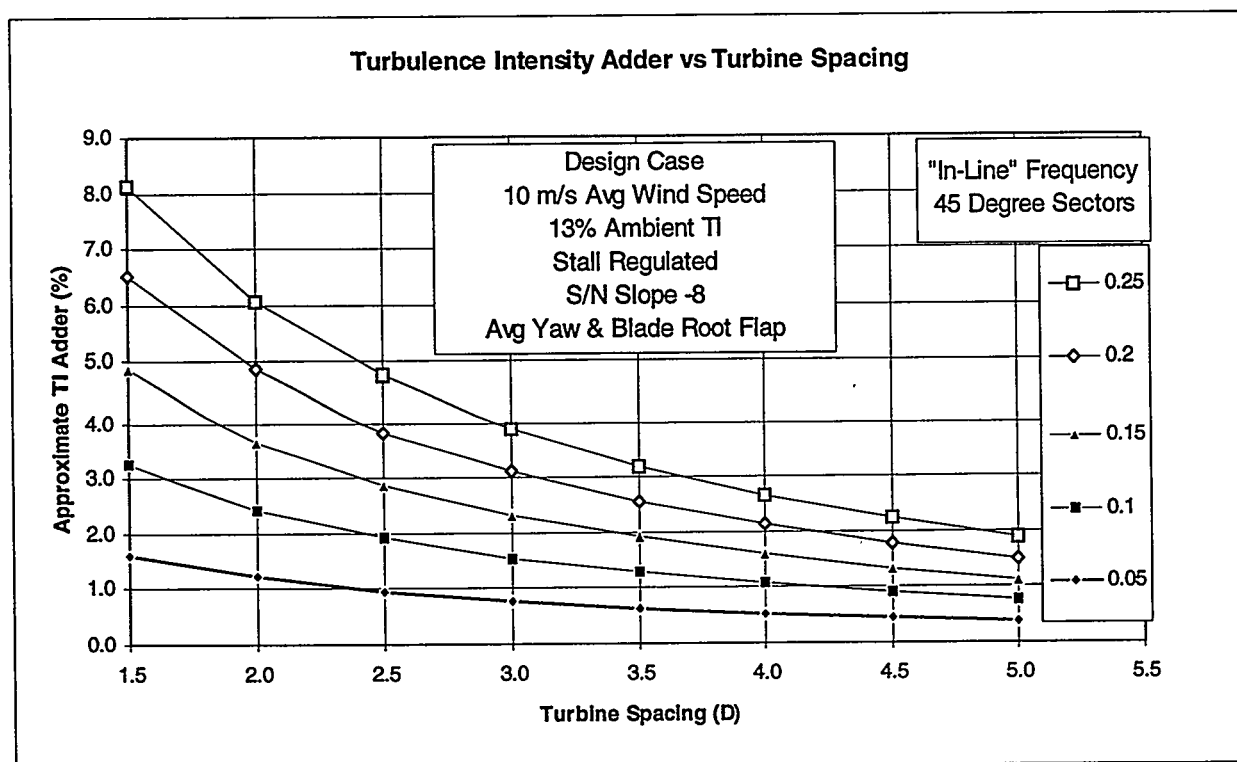


FIGURE 3 - WAKE -INDUCED TURBULENCE FOR A SINGLE ROW

GENERAL RESULTS

Table 5 summarizes the results for both single and multiple-row array cases by presenting the spacing which resulted in the lowest DCOE for each scenario. These results represent preferred spacing options under the given assumptions, and as such are just a starting point for the detailed design process where all of the external constraints must be accommodated. The reader should keep in mind that the computed energy cost is not directly comparable from case to case because the underlying wind speed has not been normalized. For example, in the single row analysis the presence of a wind speed gradient means that the selected option of 2.7D spacing for the Preferred Direction - Moderate Gradient resource scenario has a lower average wind speed than either of the other two scenarios have.

The best spacings within the rows of an array are very similar to those found in the single row analysis. A consistent trend is found in the land area column; greater total area, based on wider spacing, is associated with more broadly distributed wind directions and more nearly uniform wind speeds. The skew, which is the ratio of the spacing between rows and the spacing within rows, also changes with the resource conditions. It is interesting to note that even in the idealized Isotropic Direction - Uniform Speed Scenario where a symmetrical array spacing might be expected there are cost factors which shift the optimization to a skew greater than 2.

The relatively wide spacing selected for the Isotropic Direction Scenario creates about the same turbulence increase as the single row case and the Prevailing Direction Scenario shows a small increase for the array case. In contrast, the intermediate case shows a substantial increase to nearly 4% for the turbulence adder. Following the earlier reasoning, a layout designer in this situation could opt to increase the spacing until the turbulence adder reached an acceptable value. For example, increasing the spacing to 4Dx10D would reduce the turbulence adder to 2.5% and increase the Design Cost of Energy by 1 mil (\$0.001).

TABLE 5 - SPACING OPTIMIZATION RESULTS, 18 MW PROJECT

Wind Resource Scenario	Machine Spacing within Rows (D)	Machine Spacing between Rows or Corridor Width (D)	DCOE (\$/kWh)	Area (diameters squared)	Skew (spacing between rows/ spacing within rows)	Array Efficiency	Sample Turbulence Intensity Adder (%)
Single Row Results :							
Isotropic Direction, Uniform Speed	4.4	2.0	0.048	9	NA	0.965	2.2
Preferred Direction, Moderate Speed Gradient	2.7	2.0	0.048	5	NA	0.958	2.3
Prevailing Direction, Steep Speed Gradient	1.5	2.0	0.047	3	NA	0.948	2.0
Array Results :							
Isotropic Direction, Uniform Speed	5.0	11.0	0.048	55	2.2	0.955	2.1
Preferred Direction, Moderate Speed Gradient	3.0	9.0	0.048	27	3.0	0.933	3.7
Prevailing Direction, Steep Speed Gradient	1.8	14.0	0.047	25	7.8	0.938	2.1

CONCLUSIONS

Machine spacing optimization within regular geometric single and multiple-row arrays has been shown to be driven primarily by wind resource characteristics namely; wind direction frequencies, wind speed gradients and ambient turbulence. Due to their limited geographical extent, small clusters will tend to have weaker wind speed gradients. Incremental costs associated with changes in spacing are relatively weak determinants of optimum spacing except in cases where there is no gradient. Lateral spacings in the range of 1.5 to 5D are all potentially optimal, but only when matched to the site-specific wind resource characteristics and the machine design limits.

Careful optimization could improve a project's economic performance by several mills per kWh. The concepts discussed here lend themselves to integration with existing project cost modeling at whatever level of detail is appropriate to the case at hand. It is recommended that a model of the type discussed here be utilized throughout the project development process as a way to systematically integrate and update the technical input of various members of the team. A secondary benefit of the procedure could be an increased confidence among investors, regulatory agencies and the public at large regarding a project's viability.

Arbitrary spacing choices made without regard to wind conditions and the related optimization procedures will create additional uncertainty in lifetime predictions and may increase the cost of energy by 5% or more. In a similar fashion, other constraints imposed, for example, by customers, developers, land owners, manufacturers or regulators may have unintended consequences. A preconception that 4D is the right spacing when 2.5D yields the lowest cost of energy might be the difference between winning or losing a bid, and project options which require larger land area will not only increase development cost but may diminish the probability of success. At the same time it is important to keep in mind that the DCOE curves are often quite shallow, i.e., there is a fairly wide range over which the cost is nearly optimal. Some flexibility in accommodating external forces is often required and use of the type of model proposed would be helpful in objectively weighing the tradeoffs.

Commercially available models to predict the site-specific wake-induced turbulence need to be developed and the effects of turbulence should be included in further economic optimization work, particularly quantifying its impacts on turbine life and O&M costs. It is now common for manufacturers to offer machines customized for the annual average wind speed, thereby lowering the cost of energy. This also makes it possible to determine the incremental cost of selecting higher or lower wind speed locations. If the manufacturers were to offer machines customized for turbulence levels, it would simultaneously increase flexibility in layout design and clarify the cost impacts of various spacing options.

Finally, the general method outlined can and should be extended to other important layout optimizations such as project size, turbine model, tower height and non-uniform spacing.

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TRANSMISSION COST MINIMIZATION STRATEGIES FOR WIND-ELECTRIC GENERATING FACILITIES

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Abstract

Integrating wind-electric generation facilities into existing power systems presents opportunities not encountered in conventional energy projects. Minimizing outlet cost requires probabilistic value-based analyses appropriately reflecting the wind facility's operational characteristics.

The wind resource's intermittent nature permits relaxation of deterministic criteria addressing outlet configuration and capacity required relative to facility rating. Equivalent capacity ratings of wind generation facilities being a fraction of installed nameplate rating, outlet design studies' contingency analyses can concentrate on this fractional value. Further, given its non-dispatchable, low capacity factor nature, a lower level of redundancy in outlet facilities is appropriate considering the trifling contribution to output unreliability.

Further cost reduction opportunities arise from "wind speed/generator power output" and "wind speed/overhead conductor rating" functions' correlation. Proper analysis permits the correlation's exploitation to safely increase line ratings. Lastly, poor correlation between output and utility load may permit use of smaller conductors, whose higher (mostly off-peak) losses are economically justifiable.

Background

Northern States Power Company (NSP) is an investor-owned energy company with 1.6 million retail customers in Minnesota, Wisconsin, Michigan and the Dakotas. NSP maintains a 7,000-mile electric transmission system which integrates most of its non-contiguous load centers and generation resources and provides interconnections with adjacent power suppliers.

To provide reliable, economical electric service to its customers NSP has established a resource mix of hydro, fossil, nuclear, and wind generating capacity augmented with purchases and seasonal diversity exchanges with neighboring power suppliers. Large-scale development of the NSP wind generation resource began on southwestern Minnesota's "Buffalo Ridge" several years ago with a 25 MW development and is proceeding in a phased manner to achieve a total of 425 MW by the year 2002.

A significant burden associated with exploitation of the wind energy resource is the cost of developing the electric outlet facilities required to integrate these new generators into the existing power system. Recognizing this reality, NSP has performed technical and economic investigations to help guide the rational development of relevant design criteria and practices for addressing the atypical power system design challenges and opportunities associated with the successful utilization of wind energy resources.

This paper describes the technical and economic basis for the above-described transmission system planning practices as considered by NSP in the design of wind-electric generation outlet facilities.

Analysis

Power system design criteria

Outlet facilities for centralized, dispatchable generation resources typically consist of an on-site step-up transformer connected to a substation with multiple transmission lines providing outlet capacity. The power system design is such that

- during system intact conditions all voltages and facility loadings are within nominal ratings, and
- during post-contingent conditions (following failure of any single transmission line or transformer) all voltages and loadings are within emergency (short-term) ratings.

When generation of this conventional type is added to the power system, the appropriate substation and transmission line additions and improvements are made to ensure these performance standards are satisfied. Capital investment in transmission outlet usually amounts to a small fraction of the power plant's installed cost.

In the case of wind-electric generation, the individual turbines are typically dispersed over a significant area, in a rural setting remote from robust transmission systems. Inappropriate application of conventional planning criteria to this non-traditional resource type quickly yields very high outlet costs.

Confident that means might be found or developed to at least partially mitigate the cost burden of outlet transmission, NSP undertook a careful examination of the wind resource output characteristics, and a review of the factors which determine transmission line ratings, in an effort to produce appropriate revised design criteria which might yield appropriate operational characteristics at a more reasonable outlet cost. The following sections examine the underlying considerations upon which generation outlet facility design requirements are traditionally based, and explain the paradigm adjustments which are appropriate in the case of designing for wind generation outlet needs.

Availability

Transmission lines have very high availability (average for overhead circuits is well over 99%). Substation equipments such as transformers and circuit breakers also have very high availabilities. Despite these impressive figures, outlet facilities for dispatchable generation are nearly always designed with redundancy in mind. This is due to several considerations:

- Properly-maintained dispatchable resources have relatively high availability (generally 80 % or higher). Consequently--except for peaking facilities--transmission system component failures will usually coincide with a production period. Absent adequate redundancy, this results in system production cost penalties due to the need to generate or purchase replacement power derived from higher-cost sources. The long recovery times characteristic of steam-cycle facilities guarantee that any momentary interruption of outlet capability which results in tripping the unit off line causes several hours of production loss.
- The power pool generation reserve requirement is determined based on aggregate performance statistics of the many individual generating units. Any fleet-wide increase in tripout rate and associated reduction in individual unit availability will increase the reserve level which must be carried to satisfy any specified level of generation adequacy index, such as LOLP. Since

transmission is relatively inexpensive relative to generating capacity (generally \$100 - \$300/kW compared to \$300 - \$2,000/kW), it is a false economy to be parsimonious with respect to provision of outlet transmission capacity for large dispatchable resources. Accordingly, power pool design standards for unit outlet facilities are justifiably stringent with respect to establishing robust power system topologies which contribute very small amounts of unit output unavailability.

The combined effect of production cost penalties and generation reserve considerations is to drive transmission outlet design for dispatchable resources toward highly reliable configurations, whose premium cost is well justified by the savings which accrue from the high reliability achieved. In contrast, the following section shows how a review of equivalent capacity indicates a relaxation of certain design criteria appears appropriate in the case of wind-electric developments' outlet designs:

Equivalent capacity

In contrast to dispatchable thermal or hydraulic generation resources, the output of a wind-electric generating facility is subject to the wind's vagaries. Consequently, the "equivalent" or "accreditable" capacity (kW) for sites such as those in NSP's operating area is generally only 20 - 25% of the generator nameplate rating. It is therefore logical to design the transmission outlet facilities for the fulfillment of two goals:

- Provide adequate outlet capacity to permit full utilization of the wind generation output during system intact conditions;
- Provide adequate outlet capacity for accreditable capacity during transmission system contingency conditions.

Intentionally providing outlet transmission capability in excess of that required to satisfy these two goals is wildly uneconomical because it amounts to providing "firm" transmission for "non-firm" capacity. Since contingency conditions are present only a small portion of the operating hours per year, the resultant annual expected "trapped energy" is of minuscule economic significance compared to the annual carrying charges of the additional outlet facilities which would be required to release this last potential increment of production.

Line ratings

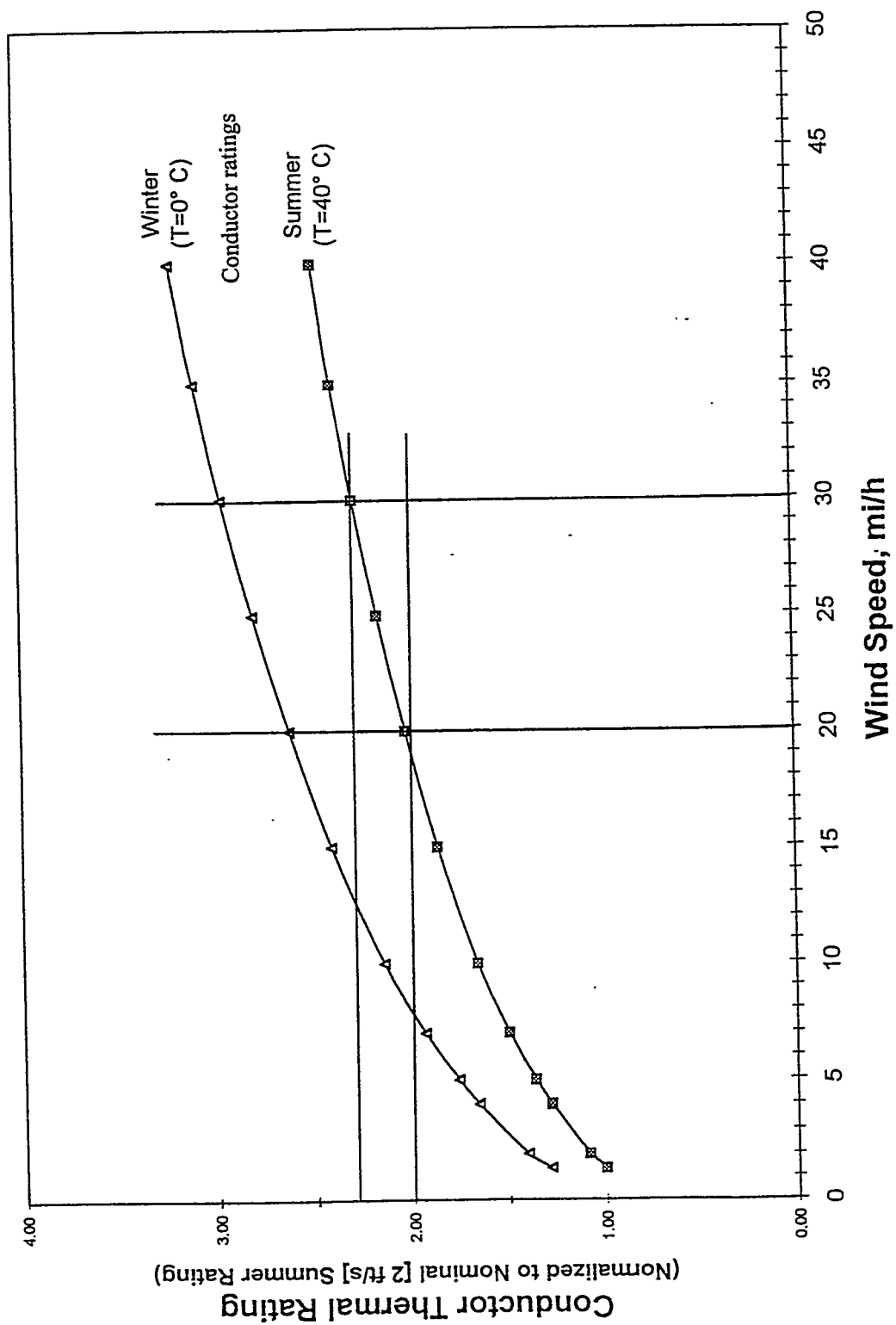
Line ratings are determined based on a desire to keep conductor operating temperatures below a certain value (often 75 or 100°C), given a set of assumed ambient conditions. The selected permissible operating temperature is based upon metallurgical considerations regarding loss of strength, annealing, or overheating of connectors. In addition, elongation due to temperature causes increased sag; this must be considered to ensure adequate clearance to ground is provided in accord with relevant safety codes.

Once the permissible conductor operating temperature is chosen, values must be selected for assumed ambient conditions, the principal parameters being air temperature and wind speed. NSP has traditionally used temperatures of 0°C (winter) and 40°C (summer) and a wind speed of 0.61 m/s (2.0 ft/s)¹ in computation of nominal seasonal circuit ratings. Since these selections influence power system reliability and public safety considerations, the temperature and wind speed values have been chosen conservatively, with due consideration to maintaining safety margins during credible worst-case combinations of meteorological conditions.

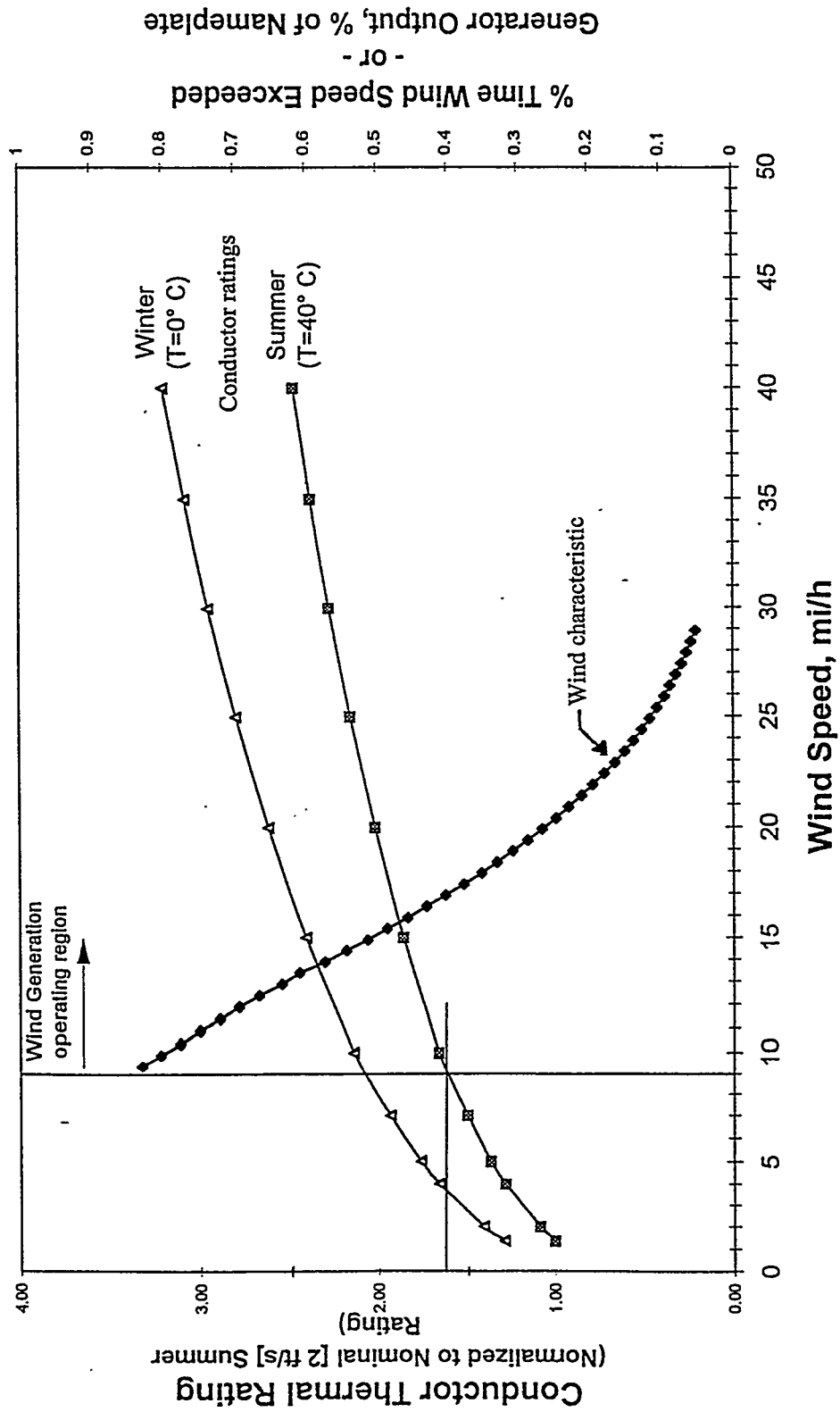
¹ This corresponds to 2.2 km/hr (1.36 mi/hr)

Graph 1

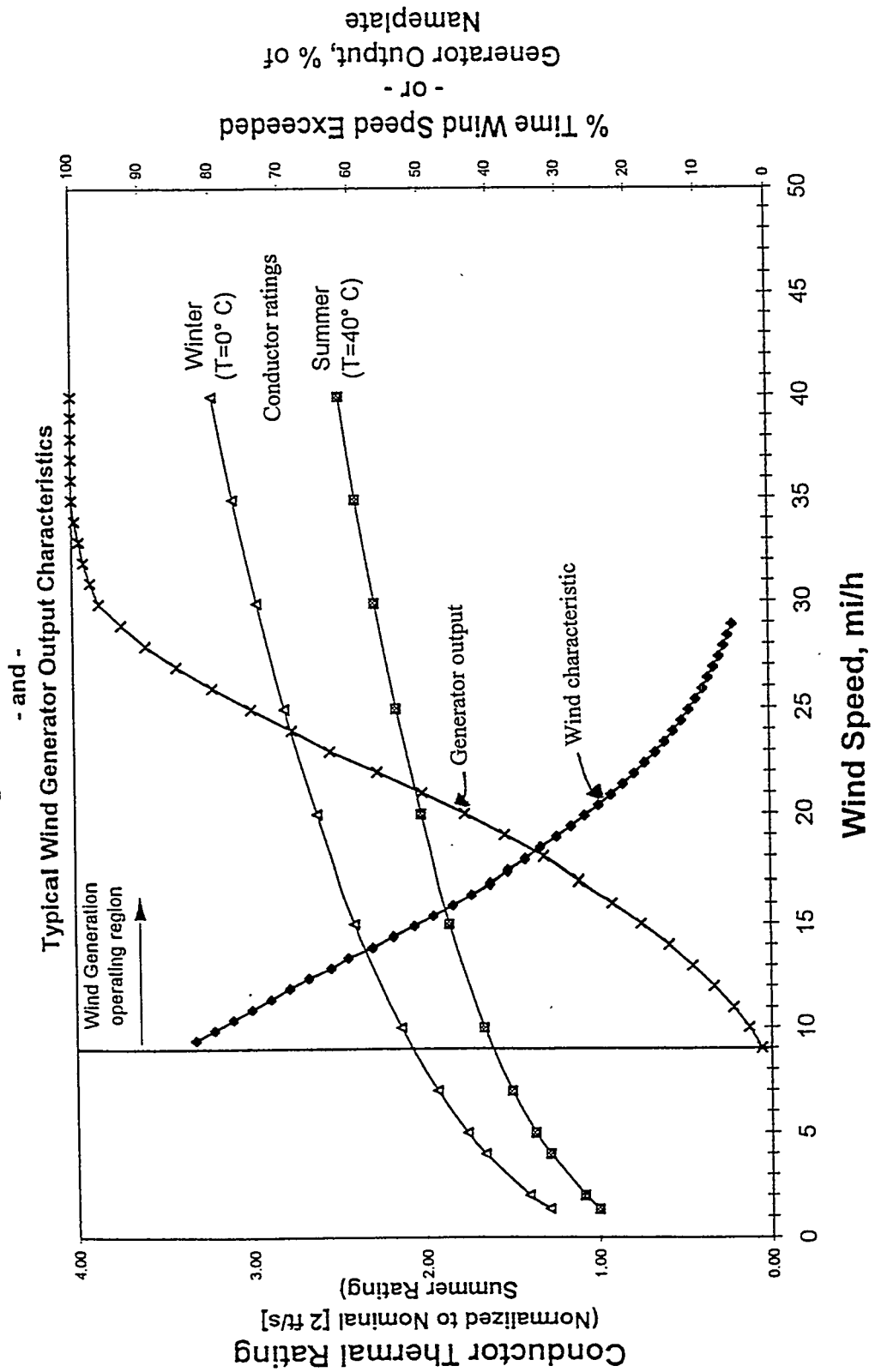
Line Rating as Function of Wind Speed (477 kcm ACSR 26/7)



Graph 2
Line Rating as Function of Wind Speed
 (477 kcm ACSR 26/7)
 - and -
Buffalo Ridge Wind Regime Characteristics



Graph 3
Line Rating as Function of Wind Speed
 (477 kcm ACSR 26/7)
 - and -
Buffalo Ridge Wind Regime Characteristics
 - and -
Typical Wind Generator Output Characteristics



Although these values are similar to those used by most other transmission entities situated in similar climates, it is clear these values (especially the wind speed) should be reviewed critically before application to a wind farm power system.

Graph 1 shows the rating of a common type and size of overhead line conductor as a function of wind speed². Clearly, as wind speed increases, the improved heat transfer due to convective cooling yields significantly increased ratings. In fact, at wind speeds over 30 km/hr (19 mi/hr) the summer season conductor rating is twice that corresponding to the 0.60 m/s nominal rating. This ratio achieves a value of approximately 2.3 at 48 km/hr (30 mi/hr), a speed which typically must be exceeded to achieve full generator nameplate output.

Graph 2 shows the effect of the wind turbine minimum cut-in speed. Presuming a minimum operating wind speed of 14.5 km/hr (9 mi/hr), it is observed the summer season conductor rating during this condition is approximately 1.6 times the nominal value.

Graph 3 shows seasonal conductor ratings, generator output, and % exceedance as a function of wind speed. From this graph and the preceding analysis it is logical to conclude there is considerable potential for wind speed-based re-rating of existing transmission circuits located adjacent to wind generation sites.

Some cautions are in order, however. For long lines leaving the wind generation area, one cannot assume the wind speed at the remote end will simultaneously be as high as the same as that enjoyed at the generation site. In fact it almost always is at least somewhat lower by dint of its being outside the area identified as having highest wind generation potential. Also, the line right-of-way must be reviewed for presence of sheltered areas due to trees, structures such as barns or warehouses, or topographic features such as bluffs. If a few such sheltered areas are discovered, one option is to simply re-conductor just those sections of line subject to the sheltered conditions; this will be much more economical than re-conductoring the entire circuit, as would be necessary if the nominal wind speed assumption were maintained.

Another potential source of increased line rating is available through higher temperature operation of the conductor. Although most transmission line owners base their circuit ratings on a selected permissible conductor temperature, undesirable outcomes do not automatically or immediately occur at slightly higher temperatures. Rather, provided that the line has adequate ground clearance to accommodate the increased sags which occur at higher temperatures, the main consideration is then one of potential for conductor metallurgical damage ("loss of [conductor] life"), and overheating of fittings. The concept of re-rating to higher operating temperature is particularly enticing in the case of circuits where high loadings would be anticipated to occur only during contingency conditions.

Several utilities are re-rating transmission circuits to operating temperatures over 100°C³. This re-rating entails a review of the original line design data, a precise field survey of as-exists conditions, and a computerized computation of line conductor-ground clearances for each span, for various possible new operating temperatures. Usually it is found that a relatively small number of spans are limiting the line to

² Line ratings computed per ANSI/IEEE Standard 738-1986 @ conductor temperature of 100°C

³ NSP, for example, is in the process of re-rating several circuits to 132°C, which yields a summer season rating increase of 24%.

an operating temperature at or near its original design value; replacing a few structures with taller ones (or lowering the ground at point of minimum clearance) in such cases permits the entire line to be re-rated to a higher operating temperature.

Occasionally it is found that a line was designed (and actually constructed) with generous clearance margins. In these fortuitous cases the uprate cost is just that of the field survey and the engineering review. On a few other occasions, the dreaded occurs: it is discovered a transmission line has inadequate clearance to satisfy code requirements at the original design temperature. This arises from errors in the original topographic survey, design errors, discrepancies in the construction, changes in ground contours or land use, or informal addition over the years of distribution circuit crossings underneath the line. In these cases remediation must be promptly scheduled and the associated costs should be considered unrelated to the wind generation development.

Losses

In the design of transmission system improvements, losses (real power and reactive power) are always taken into consideration. Real power losses represent dissipation of energy in the conductors due to the line current (amps) passing through the resistance (ohms) of the conductors. These real power losses (demand and energy) represent a financial cost to the power supplier because they require electrical production (MW and MWh) in addition to that required to satisfy the customers' utilization. Similarly, reactive power losses are caused by the line current passing through the conductors' series inductive reactance. These reactive losses must be compensated for by addition of capacitor banks or equivalent reactive generation capability.

The rational design of the collector system for a wind-electric development will properly balance the predicted incremental cumulative present value cost of losses against the incremental cumulative present value of the costs associated with additional capital investment required to achieve a lower level of losses. Although it may at first be surprising, the results of economic analyses performed for the purpose of minimizing cumulative net present value cost to the utility will usually tend to strongly suggest the collector system economics are optimized by minimizing the number of substations and constructing a few, long, high voltage feeders of high ampere rating.

These characteristics can result in relatively high losses (15 - 25% at peak loading) on some feeders compared to typical load-serving feeders constructed elsewhere. This observation can elicit premature conclusions that this represents an intolerable, alarmingly high loss level, and that "something must be done" to obtain loss levels closer to those typical of "normal" load-serving feeders (2 - 4 %). Careful review of the economics, however, confirms that economically-optimal loss levels for such collector systems are substantially higher than those for ordinary load-serving feeders. Here's why:

- The capacity factor of most wind generation is relatively low (around 30%); consequently, the load factor of the losses is low, although the distribution of the loss magnitudes is skewed toward the higher values due to the wind turbines' minimum start-up speed.
- The vacillations of wind-derived energy dictate that the correspondingly-fluctuating losses be compensated for by adjusting output levels of dispatchable generation resources. This means the energy associated with losses incurred on wind collector system feeders is most properly priced against average system incremental production cost, not a price associated with wind generation facility energy output.

- There is typically poor correlation between wind generation output level and system incremental production cost. (Wind generation output is usually not well correlated with customer load level, which is the primary driver of system incremental production cost.) This means the peak collector system losses fortunately usually occur during the power system's off-peak periods, when replacement energy is available at reasonable cost. Consequently, a probabilistic analysis shows the relatively high losses during peak production periods will predominantly be compensated for by generation elsewhere at relatively low cost. This is in contrast to regular load-serving feeders, where peak losses occur during system load peaks and must be supplied from high incremental production cost generation resources.
- Capacity value of demand (kW) losses occurring on the wind collector system is negligible. This is because any incremental losses occurring during periods when output is higher than equivalent capacity value (say, 20% of nameplate rating) do not cause the need for installation of compensatory generating capacity elsewhere: losses associated with unaccreditable capacity do not cause need for accreditable capacity. Since feeder losses are proportional to the square of feeder current, losses at 1/5 (20%) of full load current or lower are only 1/25 of those occurring at peak loading. Consequently, even if full-load losses are as high as 25% of input, the losses at or below accreditable levels do not exceed 1% of input kW.

Properly interpreted, the results of a methodical engineering economic analysis lead to the conclusion that for a wind development's collector system it is economically advantageous to design for peak feeder loss levels substantially higher than those optimal for typical load-serving feeders.

Conclusions

Achieving the economically-optimal design for a wind-electric generating facility's electrical outlet facilities requires proper consideration of

- the generation's operational characteristics and resultant equivalent capacity value;
- transmission and generation system component availabilities;
- the effect of wind on overhead transmission line capability;
- the probable incremental system production cost of losses.

Proper accounting for the above characteristics through probabilistic, value-based analyses allows for minimization of the costs (capital- and loss-related) associated with the outlet facilities required for successful operation of a wind-electric generating development.

ANTI-DOUBLE DIPPING RULES FOR FEDERAL TAX INCENTIVES

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Political as well as technological changes are now reshaping the electric utility industry. While accommodating these changes, state legislative and regulatory agencies have the opportunity to promote public policies. In this regard, various state entities are evaluating appropriate incentives for renewable energy development so as to introduce greater competition in electric generation. For example, the California legislature is considering a supplemental production payment and the State of Iowa has instituted a low-interest loan program for wind and other alternative energy generation. By complementing the existing federal tax incentives, state incentives can spur the wind industry's growth.

If structured in the wrong way, however, state assistance programs will undercut the value of the federal tax incentives. The federal anti-double dipping rules apply to certain state programs. If a developer utilizes the wrong type of state assistance for a wind project, the anti-double dipping rules will reduce the federal tax incentives and this in turn will decrease the project's profitability. Rather than suffer these results, very few if any developer will use the state program. Despite the time and effort a state may expend to enact a program for alternative energy development, the state assistance will be ineffectual. This paper reviews the counterproductive results which state assistance can have on a wind project because of the federal anti-double dipping rules.

The primary federal tax incentives for wind energy commercialization are: (1) the accelerated 5-year depreciation allowance and (2) the 1.5 cent per kilowatt hour production tax credit. Although the American Wind Energy Association is working to extend the expiration date, it should be emphasized that the current deadline for the federal production credit is fast approaching; a wind project must be placed in service before July 1, 1999 to qualify for the credit. Past WINDPOWER proceedings have reviewed the qualification requirements for the production credit and the depreciation allowance. This paper does not repeat but instead builds on those earlier discussions.

Federal tax law contains anti-double dipping rules to prevent excessive reliance on government assistance. The purpose of these rules is to have the taxpayer, who claims the federal tax benefits, pay for a substantial portion of the project with personal funds; that is, the investor must have personal funds at risk in the project. Without this requirement, an investor might combine federal and state government programs to pay for nearly all the cost of an energy project.

To preclude this situation, the federal anti-double dipping rules will reduce the value of federal tax incentives for a wind energy project in proportion to the amount of certain

state aid. Although state assistance can enhance the project's cash flow, the wrong type of state incentive will reduce the rate of return significantly. The precise effect of a state program must be evaluated for each project.

I. Impact of State Assistance on Federal Tax Incentives.

To see how the federal anti-double dipping rules can affect a project, let us compare three hypothetical cases. The first case employs no state assistance to provide a base line for comparison. The second case uses a state no-interests loan which reduces the federal production credit. The third case utilizes a state grant which reduces both the production credit and the depreciation allowance. The second and third cases illustrate two ends of the spectrum where the effect on the internal rate of return is minimal and where the effect is drastic. All three cases are based on the following assumptions:

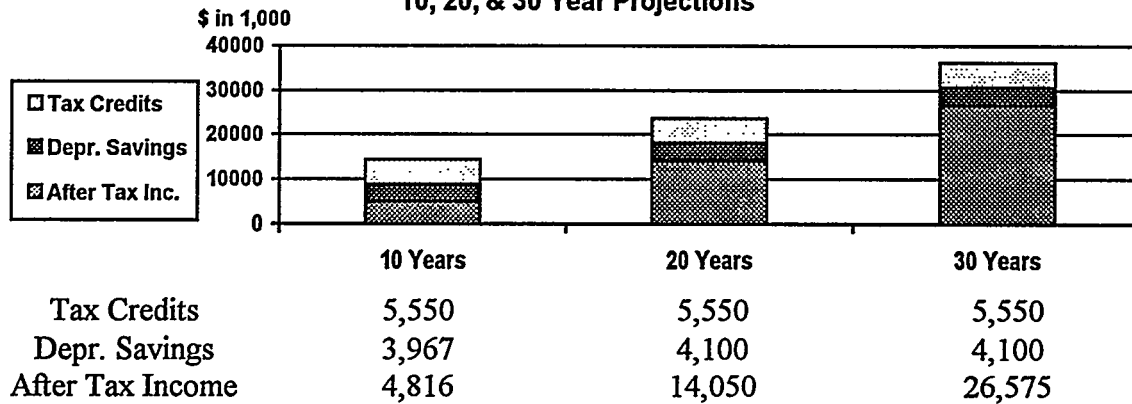
1. 10 MW windfarm.
2. \$10,000,000 capital cost.
3. January 1, 1998, place-in-service date.
4. 30,000,000 kWh annual power production.
5. 4.5 cents per kWh energy payment rate.
6. 1.2 cent per kWh cost for operational, maintenance, and miscellaneous expenses.
7. 3% annual inflation rate and adjustment for:
 - a. Energy payment.
 - b. Operational costs.
8. Depreciation for regular tax -- MACRS 200% declining balance.
 - a. 90% (\$9,000,000) 5-year wind equipment.
 - b. 10% (\$1,000,000) 15-year property.
9. 35% federal regular corporate income tax rate.
10. 6% state corporate income tax rate.
11. 9.6% discount rate for NPV calculations.
12. Taxpayer is not subject to the alternative minimum tax and can fully utilize the project's depreciation deductions and tax credits currently.

Although the three cases are based on an assumed 3% annual rate of inflation, the federal production credit is adjusted by the gross domestic price implicit price deflator for the preceding year. This leads to a slightly lower adjustment. So, let us assume that the per kilowatt hour federal production credit will be as follows:

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Cents	1.7	1.7	1.8	1.8	1.8	1.9	1.9	1.9	2.0	2.0

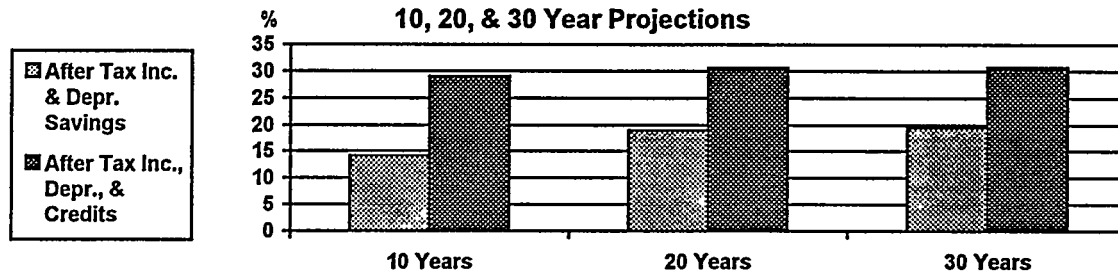
In Case 1, the investor finances the \$10 million capital cost half with equity and half with debt. The \$5 million debt is a level payment loan to be repaid over 12 years at 10% interest. The project's net income (after state and federal income tax), its depreciation tax savings, and its federal tax credits are summarized in Chart 1.

Chart 1: Case 1 Without State Incentives
After Tax Income, Depreciation Savings, & Production Credits
10, 20, & 30 Year Projections



An internal rate of return analysis can better evaluate these numbers and compare them with alternative investments. Chart 2 shows the internal rate of return at 10 years, 20 years, and 30 years for Case 1. We can see from this chart how the production tax credit materially enhances the project's rate of return.

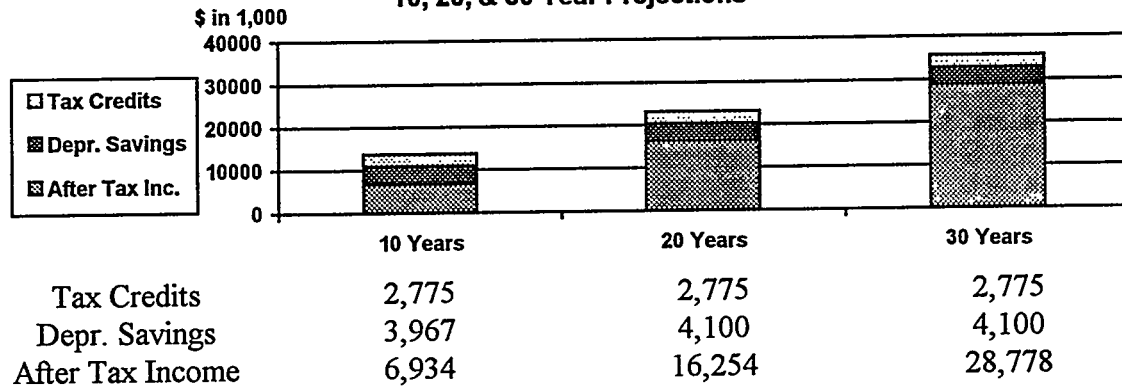
Chart 2: Case 1 Without State Incentive
Internal Rate of Return
10, 20, & 30 Year Projections



After Tax Inc. & Depr. Savings	14.20	18.95	19.64
After Tax Inc., Depr. Savings & Cr.	29.02	30.53	30.65

In Case 2, instead of a \$5 million, 12 year, 10% loan, the project uses a no-interest loan from a state energy program. The loan is to be repaid over the same 12 year period. The investor will use the loan to finance 50% of the project's capital cost. Chart 3 summarizes the project's net income (after state and federal income tax), the depreciation tax savings, and the federal tax credits.

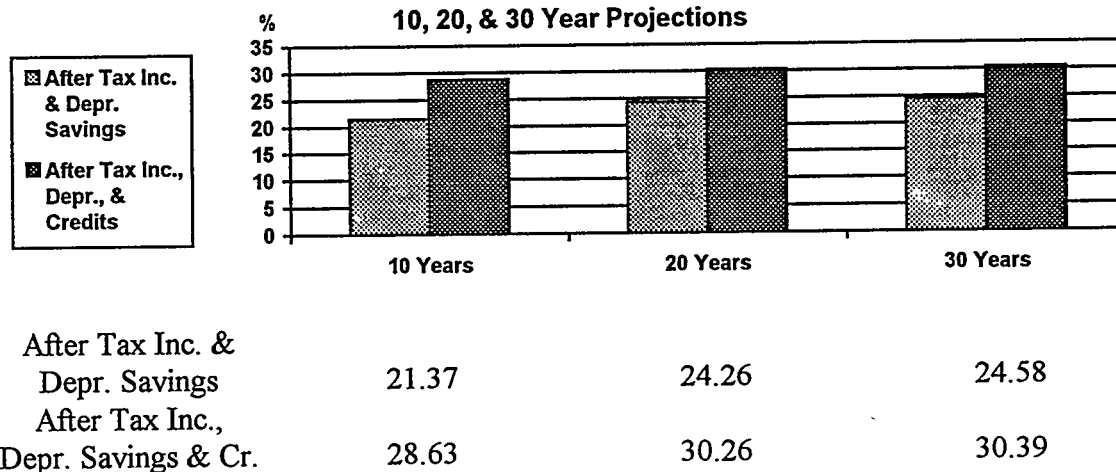
Chart 3: Case 2 Using State No-Interest Loan
After Tax Income, Depreciation Savings, & Production Credits
10, 20, & 30 Year Projections



As Chart 3 shows, the subsidized state financing cuts the production credit by half. The anti-double dipping rules require that the credit be reduced by the percentage of the project's capital cost which comes from the subsidized financing. Since the state no-interest loan covers 50% of the capital cost, the production credit is reduced in the same proportion. In contrast, the depreciation deduction in Case 2 with state financing is the same as in Case 1 which has no state assistance. The basis for depreciation is the project's cost which remains \$10 million.

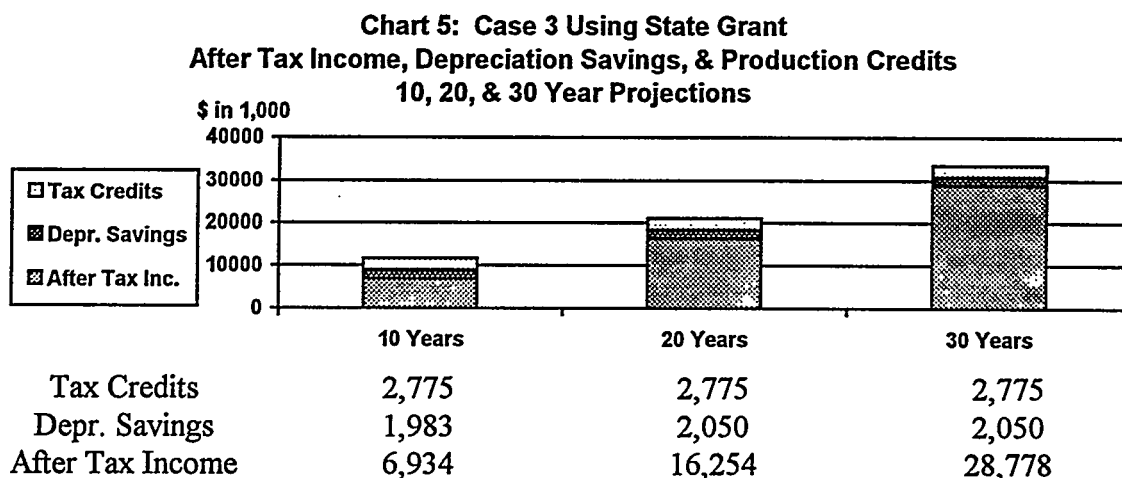
The state financing assistance enhances the project's cash flow, because the project now does not need to service any debt payment. With no debt service payments to be made, the project's net income increases handsomely as Chart 3 indicates. Despite the loss of half the production credits, the increased net income almost compensates. Chart 4 shows that the overall internal rate of return in Case 2 closely approaches the rate of return in Case 1. The percentage rate of return in Case 2 is lower by .39 in the first 10 years, by .27 over a 20 period, and by .26 over a 30 year period. The enhanced income due to the no-interest loan nearly makes up for the credit reduction.

Chart 4: Case 2 Using State No-Interest Loan
Internal Rate of Return
10, 20, & 30 Year Projections



Case 2 assumes that the state alternative energy assistance provides an interest-free loan. If the assistance takes the form of a low-interest loan, the effect would not be as benign. The payment of debt service, even lower-rate debt, will reduce net income and affect the internal rate of return. Time constraints foreclose a full presentation of the data, but if the 12-year loan in Case 2, instead of being interest free, carried 6.5% interest, the percentage internal rate of return would be lower than in Case 1 by 4.49 over the first 10 years, by 3.82 over 20 years, and by 3.71 over 30 years. This shows how the particular facts will affect the outcome.

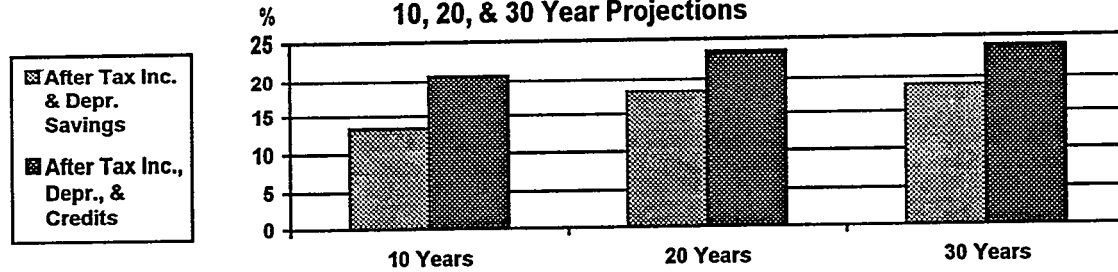
In Case 3, the reduction in the internal rate of return is even greater. Rather than incur a \$5 million loan, the project uses a state grant to cover 50% of the project's capital cost. Chart 5 summarizes the project's net income (after state and federal income tax), the depreciation tax savings, and the federal tax credits.



In Case 3 the \$5 million state grant pays for half the cost of the project. The taxpayer's portion of the capital cost is reduced from \$10 million to \$5 million. As reflected in Chart 5, the grant causes not only the loss of half the production credits but also the loss of half the depreciation deductions. As explained earlier, the tax basis for depreciation is the taxpayer's cost. The investor in Case 3 pays only \$5 million of the project's capital cost and this is the investor's depreciation basis.

In contrast with Case 1, the project in Case 3 enjoys increased cash flow and net income because of the state grant. But the reduced depreciation deductions and reduced tax credits will lower the internal rate of return percentage -- shown in Chart 6 -- by 8.25 over the first 10 years, by 7.00 over a 20 year period, and by 6.78 over a 30 year period. The increased net income does not compensate for the lost tax benefits.

Chart 6: Case 3 Using State Grant
Internal Rate of Return
10, 20, & 30 Year Projections

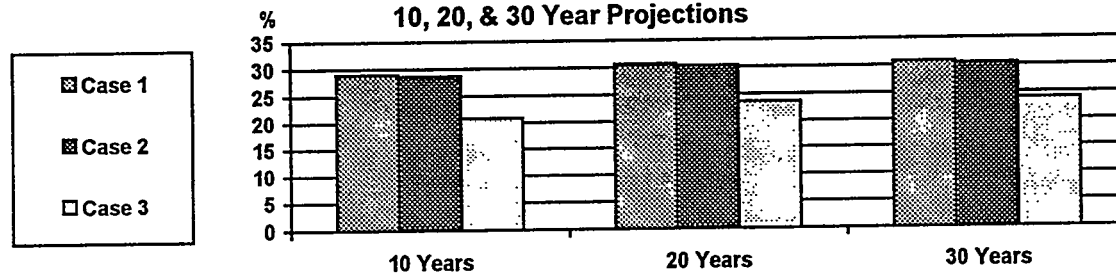


After Tax Income & Depr. Savings	13.34	18.14	18.88
After Tax Inc., Depr. Savings & Cr.	20.77	23.53	23.87

Chart 7 compares the internal rate of return in the three cases. We see that the state no-interest loan in Case 2 while reducing the project's federal production credit barely affects the overall internal rate of return. Here, the investor needs to weigh the benefit of lower debt service payments against the relatively small erosion in the rate of return.

In contrast, we see that the state grant in Case 3 by reducing both the federal production credit and the depreciation deduction cuts the overall internal rate of return significantly. The state incentive here has a very detrimental effect. An investor who can fully and currently utilize the federal tax benefits will avoid using the state grant program.

Chart 7: Comparison of Cases 1, 2, & 3
Internal Rate of Return
10, 20, & 30 Year Projections



Case 1	29.02	30.53	30.65
Case 2	28.63	30.26	30.39
Case 3	20.77	23.53	23.87

Whether an investor can utilize all the federal tax benefits currently is a big assumption. Many taxpaying investors are subject to the alternative minimum tax and cannot benefit fully from depreciation deductions and production credits. Where the federal tax benefits are of little benefit, the anti-double dipping rules' reduction of the tax benefits will correspondingly have little impact. In this situation, a state's no-interest energy loan or

grant may outweigh the reduction of the federal tax benefits. As earlier pointed out, the state no-interest loan or grant will enhance the project's cash flow as Charts 8, 9, and 10 indicate.

Chart 8: Comparison of Cases 1, 2, & 3

10 Year Projection

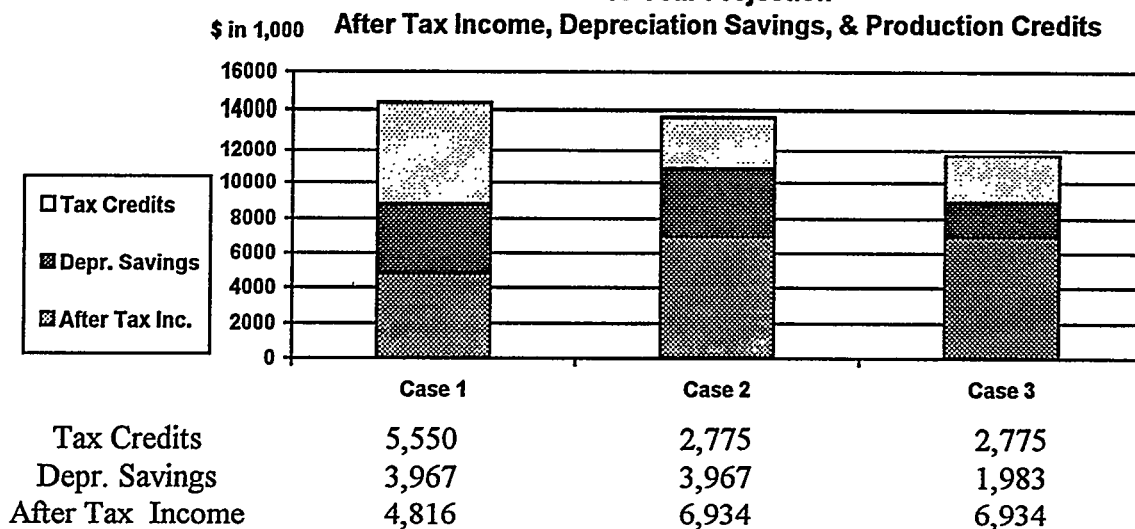
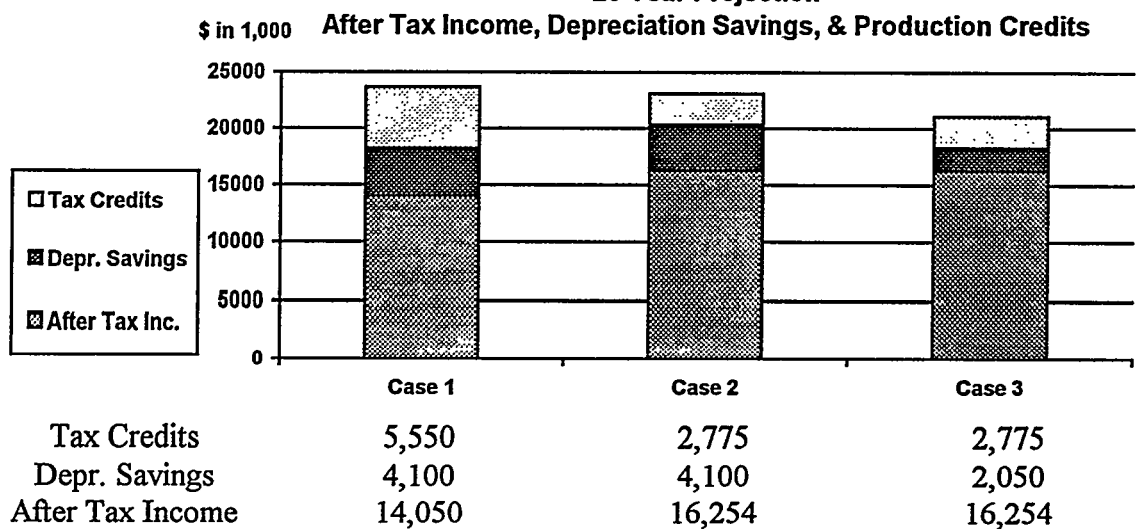
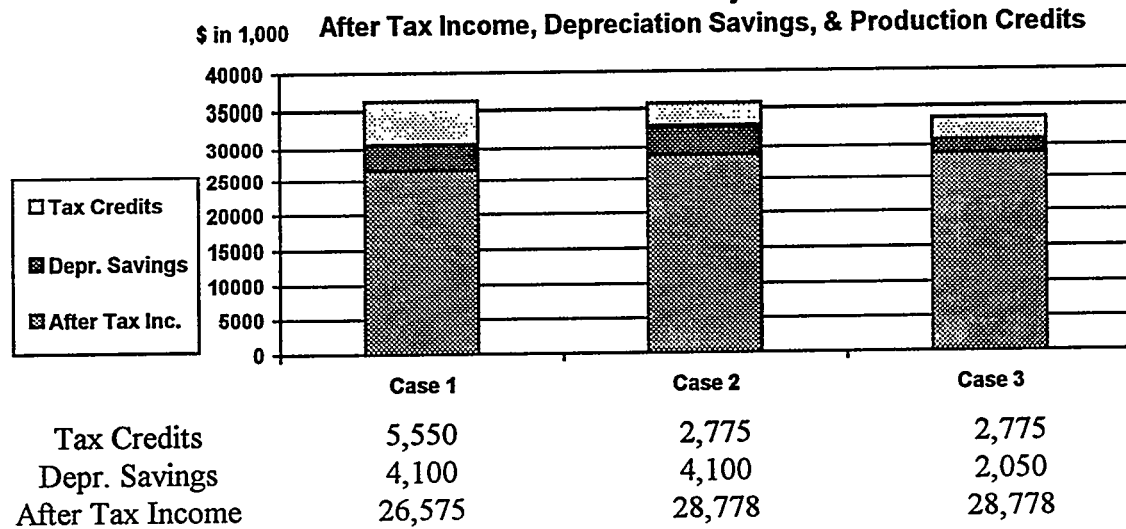


Chart 9: Comparison of Cases 1, 2, & 3

20 Year Projection



**Chart 10: Comparison of Cases 1, 2, & 3
30 Year Projection**



Whether over 10, 20, or 30 years, the total net income, depreciation savings, and the production credits in Case 2 is only slight less than in Case 1, whereas the total in Case 3 is significantly less than in Case 1. But if we assume that the project owner cannot utilize the production credit nor the depreciation deduction, then the net income stream becomes far more important than the tax benefits. As Charts 8, 9, and 10 show, the net income in Case 2 with the state no-interest loan and in Case 3 with the state grant are far greater than the net income in Case 1.

As the comparison indicates, certain state incentive programs like an interest-free loan have very modest negative effect on the project's internal rate of return. In actuality, however, state assistance programs are far more likely to adopt a partially subsidized interest loan program or a low-interest loan program instead of an interest-free loan program. In the case of a 6.5% low-interest loan or an outright state grant covering half the project's capital cost, the state assistance would have a measurable negative effect.

Again, time constraints limit the number of cases that can be presented. Let me stress, however, that the analysis is highly dependent on the particular circumstances. If a state assistance program did not trigger the federal anti-double dipping rules, that state program could be a very effective incentive. For example, assume that a state offered a production incentive payment of 1 cent per kilowatt hour of electricity produced and sold. Assume that this incentive covers the initial five years of a facility's production. If the anti-double dipping rules do not apply to this incentive, the state assistance would boost the internal rate of return percentage in Case 1 by 5.93 over 10 years, 5.41 over 20 years, and 5.35 over 30 years.

The specific state assistance program and the investor's tax status will determine the exact impact of the anti-double dipping rules. Where the investor can fully utilize a project's federal tax benefits, the anti-double dipping rules will materially reduce the project's

profitability as in Case 3. On the other hand, where the state assistance compensates for the lost federal tax benefits or where the investor cannot use the federal tax benefits in a Case 2 situation, the anti-double dipping rules will have negligible impact; here the state assistance will enhance the project's cash flow and profits.

Generally speaking, however, wind developers seek to maximize the tax benefits, because the likely investors will fully utilize them. Developers will thus avoid state assistance programs which endanger the federal tax benefits and reduce the project's rate of return. Since very few developers will utilize such assistance, the state programs will in all likelihood be ineffectual in promoting alternative energy development.

II. State Assistance That Reduce the Federal Tax Incentives.

In the above examples, we have seen how state assistance triggers the federal anti-double dipping rules; we have also seen how the resulting reduction of federal depreciation deductions and tax credits affects a project's profitability. What types of state assistance will trigger this reduction? The federal anti-double dipping rules are broad and cover a range of state assistance. The federal production credit is to be reduced for assistance which the wind project receives from a:

- A. Grant by a federal or state agency.
- B. Proceeds from a state or local government tax-exempt bond.
- C. Subsidized energy financing provided or indirectly by a federal, state, or local program.
- D. Other tax credit.

The amount of the federal production credit will be reduced in proportion to the total project cost which is covered by these forms of assistance. Similarly, the project's depreciation base is reduced by grants.

III. State Assistance That Will Not Reduce the Federal Tax Incentives.

What kind of assistance programs can a state provide to encourage wind development? The Internal Revenue Service has not had to face this question yet. In response to a telephone inquiry, a tax law specialist at the IRS National Office said that the statutory language broadly covers any grant from a state or local government agency. Since money is fungible and inter-changeable in this way of thinking, the name of the grant or the purpose of the grant is immaterial. Whether the assistance is called a capital cost reduction grant to reduce acquisition cost or a supplemental production payment to increase the project's sales income, the grant or payment will reduce the federal tax credit.

This position, which is an initial reaction to telephone inquiry, is too expansive in my opinion. Without studying the matter, the Service's initial answer does not take into account the congressional policy and legislative history behind the renewable energy incentives. The legislative policy had focused on the purpose and use of the state

assistance. The congressional intent behind the anti-double dipping rules was to offset certain capital assistance programs; Congress did not forbid all state assistance programs.

Based on the congressional policy, legislative history, and interpretation of comparable provisions, it is my view that the anti-double dipping rules for the wind production credit do not apply to price support payments, supplemental production payments, state tax credits, operation and maintenance assistance payments, nor to loan guarantees under state programs. This, however, is my personal opinion. The Internal Revenue Service has not ruled as to how any of these programs would affect the federal tax incentives for a wind project.

Windfarm developers need to structure their project with assurance of the tax results. Those developers who want to utilize state assistance programs will need to seek an advance ruling from the Internal Revenue Service that the state incentive will not reduce the federal tax benefits. As the above discussion demonstrates, the wrong state assistance can have a detrimental effect on the project's internal rate of return.

WINDPOWER PROJECT OWNERSHIP AND FINANCING: THE COST IMPACTS OF ALTERNATIVE DEVELOPMENT STRUCTURES

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ABSTRACT

This paper uses traditional financial cash-flow techniques to examine the impact of different ownership and financing structures on the cost of wind energy. While most large-scale wind projects are constructed, operated, and financed by non-utility generators (NUGs) via project financing, investor- and publicly-owned utilities have expressed interest in owning and financing their own facilities rather than purchasing wind energy from independent generators. A primary justification for utility ownership is that, because of financing and tax benefits, windpower may be cheaper when developed in this fashion. The results presented in this paper support that justification, though some of the estimated cost savings associated with utility ownership are found to be a result of shortcomings in utility analysis procedures and implicit risk shifting. This paper also discusses the comparative value of the federal production tax credit and renewable energy production incentive; estimates the financing premium paid by NUG wind owners compared to traditional gas-fired generation facilities; and explores the impact of electricity restructuring on financing.

INTRODUCTION

High capital costs and perceived technology and resource risks can make financing particularly difficult and costly for renewable energy projects, including windpower. This paper demonstrates the importance of financing in the windpower project development process by examining the effects of financing and ownership structure on the levelized cost of wind energy. Cost and non-cost tradeoffs among different forms of financing and ownership are explored.¹

Most large-scale wind projects in the United States have been developed and financed by private renewable energy companies, often through project financing structures. Electric output is often then sold to investor- and publicly-owned utilities under long-term contracts. Although still by far the most popular form of windplant development, alternative forms of ownership and financing are now being considered. Specifically, several U.S. publicly-owned and investor-owned electric utilities have begun to express interest in owning and financing their own wind facilities rather than purchasing windpower from independent non-utility generators (NUGs) through power purchase agreements (PPAs).² In these utility-ownership arrangements, the wind turbine equipment

¹ This paper is based on a more detailed Lawrence Berkeley National Laboratory report and journal article (see Wiser and Kahn 1996; and Wiser 1997).

² In 1994, SMUD became the first utility to *directly* own and self-finance a large-scale wind project in the United States, when 5 MW of wind capacity went on-line. Under the Utility Wind Turbine Performance Verification Program, Central and Southwest and Green Mountain Power have also developed larger wind farms. Most other utility-owned projects are of substantially smaller size (see, for example, UWIG 1994; Williams and Bateman 1995). Several

vendor/developer typically designs and constructs a project under a turnkey contract for the utility owner. The utility will also frequently sign an operations and maintenance (O&M) contract with the project developer/equipment vendor.

A number of reasons have been offered to explain utility involvement in recent and planned U.S. wind projects. One important claim is that, because of tax and financing advantages, utility ownership and financing is less expensive than contracting with private NUGs to supply wind-generated power. This paper examines that assertion by estimating the levelized cost of wind energy under three different ownership and financing scenarios: (1) private NUG ownership with project financing; (2) investor-owned utility (IOU) ownership with corporate financing; and (3) publicly-owned utility (POU) ownership with tax-exempt bond financing.³

This paper also analyzes and discusses several additional issues associated with windpower financing, including: (1) the extent to which the calculated cost savings of utility ownership are due to real financial cost reductions rather than inherent shortcomings in the analysis procedures and implicit risk shifting; (2) the comparative value of the federal production tax credit and renewable energy production incentive to different windplant owners; (3) the financing premium paid by NUG wind owners compared to traditional NUG gas-fired generation facilities; and (4) the impacts of electricity restructuring on financing a wind project. This last item is particularly important because changing regulatory and market conditions could substantially influence the financing process for wind generators.

ANALYTIC APPROACH

To model windplant cost, tax, operating, and finance variables, three cash-flow models were developed, one for each of the general ownership and financing arrangements. In all cases, the spreadsheet models assess a fictional 50 MW wind facility with specified inputs. Overall costs are then evaluated and compared on a 20-year nominal levelized cost basis in 1997 dollars.

Each spread-sheet model was developed to replicate as closely as possible actual utility and developer cost-estimation techniques: (1) a pro-forma cash-flow model is used to assess NUG ownership; (2) a revenue-requirements model is developed for the IOU ownership scenario; and (3) a cash-flow model is created to evaluate the POU scenarios. For a more thorough description of the models, see Wiser and Kahn (1996).

Table 1 shows some of the key input variables to the cash-flow models. An attempt was made to provide reasonable estimates for all inputs. The analysis assumes that capital costs, O&M, land expenses, insurance, and administration and management fees are the same for all three ownership scenarios. Because this assumption is not expected to hold perfectly (because of risk transfers, mark-ups, etc.), the utility cost savings estimated in this paper most likely provide an upper bound to the cost savings actually available from utility ownership of wind facilities.

utility-owned projects are currently under development, some of which may be multi-megawatt facilities.

³ This paper does not consider the full range of financing structures that can be used for distributed, customer-sited facilities and cluster developments, but instead focus' on those arrangements typical of large-scale windfarms in the U.S.

TABLE 1. MODEL INPUT ASSUMPTIONS

Project Variable	Value
Project Size	50 MW
Capacity Factor	30%
Installed Capital Cost (\$1996)	\$1000/kW
O&M Expense (\$1997)	\$17/kW-yr
Land Expense (\$1997)	\$190,000/yr
Insurance Expense (\$1997)	\$75,000/yr
Administration and Management Fee (\$1997)	\$50,000/yr
Property Tax (IOU and NUG)	1.1% of book value
Production Tax Credit (\$1992) (IOU and NUG)	1.5¢/kWh
Renewable Energy Production Incentive (\$1992) (POU)	1.5¢/kWh
Tax Depreciation (IOU and NUG)	5 yr MACRS
Effective Income Tax Rate (IOU and NUG)	38%
Inflation Rate	3.5%

DIFFERENCES AMONG DEVELOPMENT STRUCTURES

NUG Ownership: Private power producers have generally financed projects on a stand-alone, project finance basis. Under project financing, lenders look primarily to the cash flow and assets of a specific project for repayment rather than to the assets and credit of the promoter of the facility. To reduce the risk associated with project default, lenders usually require that a project maintain a minimum ratio of available cash to total yearly debt service, called the debt service coverage ratio. Because debt is generally considered to be less costly than equity, there is a tendency for developers to maximize debt leverage, but this tendency is limited by debt service requirements. The benefits of project financing include: (1) debt is typically non- or limited-recourse and therefore does not have a substantial impact on the balance sheet or creditworthiness of the parent company; and (2) capital structure is quite variable, allowing developers to optimize debt leverage. The negative aspects of project financing include higher transaction costs, legal fees, and debt and equity costs, and a greater array of loan covenants (Nevitt 1983). NUG owners of U.S. wind projects currently receive two key federal tax incentives: the production tax credit (PTC) and 5-year accelerated depreciation.

IOU Ownership: IOUs depend primarily on corporate (internal) financing, which relies on the attractiveness of a firm's balance sheet and prospective cash flows. Therefore, when IOUs borrow money from public markets, the support for their credit comes from the income stream of their entire asset base. Corporate financing lacks the degree of asset-specificity found in project financing. The apparent benefits of IOU corporate financing include: (1) lower debt and equity costs are typically used to evaluate projects; (2) longer debt amortization; and (3) no project-specific debt service requirements. The most important cost of IOU ownership may be a less flexible capital structure. IOU income taxes are also "normalized," and are therefore expensed differently than

NUG income taxes. As with NUG ownership, IOUs receive the PTC and 5-year accelerated depreciation.

POU Ownership: Publicly-owned utilities can and have used both internal and project financing for power plant development; this paper evaluates both alternatives. The key difference between these two financing types is the extent to which the public utility provides additional security and collateral to the lender beyond the power project itself and its power sales contract. As with IOU corporate financing, credit support for internal financing comes from the entire asset base of the utility. To reduce "corporate" liabilities and risks, however, U.S. POUs have also used project financing in recent years. In this scenario, the POU creates a subsidiary (e.g., a Joint Powers Authority) to own and finance the power project and arranges to purchase its power through a PPA. Costs calculated under the project financing scenario are typically higher than under internal financing because of increased project-specific debt costs. In general, the benefits of public ownership include: (1) use of 100% tax-exempt debt; (2) longer debt amortization period; (3) no income taxes; and (4) reduced property taxes. There are two key disadvantages of public ownership. First, because income taxes are not paid, publicly-owned utilities cannot receive some of the tax advantages afforded to NUG and IOU owners of wind projects, namely accelerated depreciation and the federal PTC. Second, although public entities can receive an equivalent cash production incentive in lieu of the PTC, the yearly funding for this renewable energy production incentive (REPI) is subject to Congressional appropriation. Because of the uncertainty associated with this process, POU renewable energy projects are frequently evaluated as if the incentive were not available (Wiser and Pickle 1997). For the analysis presented in this paper, the levelized cost of windpower in the public ownership scenarios is therefore estimated under two input cases. The first assumes full expectation of receiving the 10-year, 1.5¢/kWh REPI. The second assumes that the utility has no expectation of receiving any outlays from this program.

The key financing and tax differences among the various ownership and financing structures are summarized in Table 2. These estimates come from a variety of sources, including personal communications with wind project

TABLE 2. FINANCING AND TAX DIFFERENCES AMONG DEVELOPMENT STRUCTURES

Variable	POU Ownership			
	NUG Ownership	IOU Ownership	Internal Finance	Project Finance
Capital Structure	Flexible	50% equity 50% debt	100% debt	100% debt
Debt Interest Rate	9.5%	7.5%	5.5%	7.5%
Debt Amortization	12 years	20 years	20 years	20 years
Debt Repayment Schedule	Mortgage-Style	Straight-Line Declining Rate-Base	Mortgage-Style	Mortgage-Style
Debt Service Coverage Ratio	Minimum 1.4	No project-specific requirement	No project-specific requirement	Effectively, no project-specific requirement
Equity Cost	18%	12%	n/a	n/a
Property Tax	Levied on total value of facility	Levied on total value of facility	Levied only on value of land	Levied only on value of land
Income Tax	5-yr depreciation	5-yr depreciation; normalized	None	None
Production Incentive	PTC	PTC	REPI	REPI

developers, investor- and publicly-owned utilities, investment banks and lenders, and various publications (see Wisner and Kahn 1996). The values are broadly representative of those currently used in the cost-estimation techniques employed by utilities and private developers.

ANALYSIS RESULTS

The estimated cost of a wind project under different ownership and financing arrangements is shown in Figure 1. Although the absolute value of these levelized cost estimates depends on project-specific input cost and performance assumptions, the relative cost advantages shown below should not be substantially affected by these input assumptions.

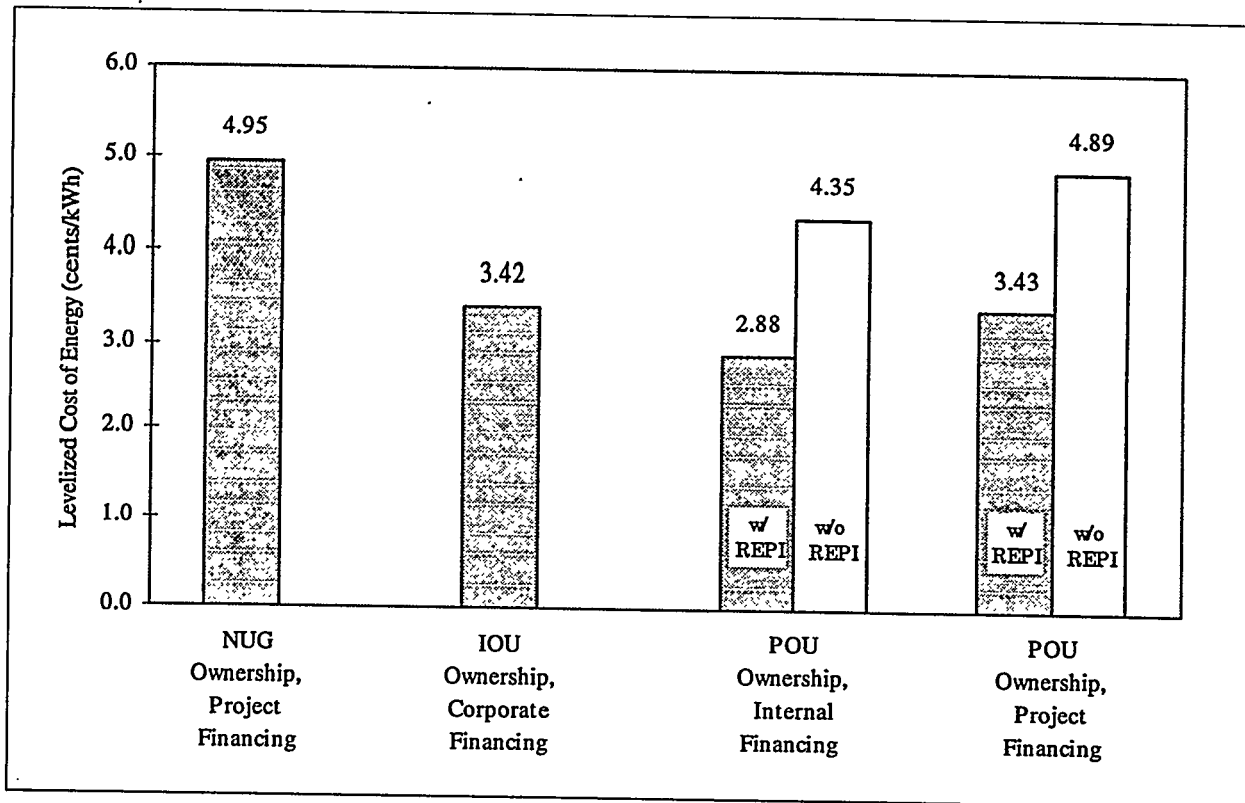


FIGURE 1. IMPACT OF OWNERSHIP STRUCTURE ON WINDPOWER PROJECT COSTS

Using traditional cost-assessment techniques, it appears as if IOU and POU ownership can result in substantial cost savings. Compared to the NUG ownership, project financing structure, IOU ownership reduces apparent levelized costs by approximately 30% (1.5¢/kWh).

Assuming the 10-year REPI payments are included in the cost analysis, the public ownership, internal financing scenario is estimated to be the lowest-cost method to develop wind projects (2¢/kWh less than NUG ownership, a savings of 40%). Clearly, low-cost debt financing, tax exemptions, and the lack of project-specific debt service requirements lower estimated costs substantially. Even without REPI payments, this ownership and financing arrangement costs 12% (0.6¢/kWh) less than the NUG ownership case. However, in this “no-REPI payment” scenario, IOU ownership is the lowest cost alternative (because the additional financing advantages afforded to POU owners do not offset the loss of the REPI).

Debt costs are more substantial when the POU uses project financing. If REPI payments are included, this scenario still costs much less than contracting with a NUG to supply windpower (the nominal levelized cost is approximately equivalent to that for the IOU case and is 30%, or 1.5¢/kWh, cheaper than NUG ownership). If REPI payments are not included in the cash-flow model, the estimated cost of a project financed, publicly-owned windplant is approximately the same as that of a NUG-owned facility.

These results provide an upper bound to the potential cost savings associated with utility ownership because turbine mark-ups and performance guarantees would likely result in higher input costs in the utility ownership arrangements than with NUG ownership. Nonetheless, this analysis suggests that the most common form of U.S. wind development, namely NUG ownership with project financing, is also the most costly. The results seem to validate the claim that windpower costs can be reduced through direct utility ownership.

OWNERSHIP TRADEOFFS AND RISK TRANSFERS

This paper has, thus far, emphasized the potential cost savings associated with utility ownership and financing of wind projects, but direct ownership may have additional benefits to electric utilities: (1) in traditional utility structures, it allows a utility to rate-base the project and earn a return on their investment; (2) it provides the utility direct experience with the technology; and (3) it can enhance a utility's image because renewables are generally viewed favorably by the public.

It is important to consider, however, whether utility ownership and self-financing of wind turbine power plants is truly cheaper than power purchases from entities using project financing or, instead, if utility ownership and economic analysis procedures simply conceal the true costs and risks of wind development. The cost savings of utility ownership are at least partially offset by the increased risk to utility shareholders and ratepayers in utility-ownership scenarios. In project finance, there is an explicit recognition and pricing of project-related risks. With utility ownership, on the other hand, many risks are implicitly passed on to and borne by ratepayers. Specifically, ownership of generation facilities results in an increased performance risk liability compared to contracting with independent power suppliers through PPAs. Contract terms can be developed to minimize utility risk. For example, at a cost, turnkey construction contracts, performance guarantees, and fixed-price O&M contracts can all mitigate project risks for the utility owner (Duvall and Vachon 1994). Despite the risk reduction potential of these mechanisms, however, it is unlikely that contract terms can be developed to entirely eliminate all risks associated with direct project ownership.

The analysis techniques applied in this paper, which mimic actual methods used by utilities and NUGs, do not all accurately reflect these risk transfers. Specifically, in IOU and internal finance POU cost assessment, the overall credit rating of the utility is used to estimate debt and equity costs, rather than the project-specific debt and equity costs used in NUG analysis. This approach ignores the variance in risks associated with different projects and therefore the marginal impact of different investments on financing costs (Awerbuch *et al.* 1996; Wiser 1997). If financial risks are higher for wind projects than for other utility investments, then use of corporate average debt and equity costs will underestimate the *real* costs of utility ownership by concealing the impact of the wind investment on the marginal cost of capital to the company. While utility ownership (especially POU ownership) may still be more attractive than purchasing power from NUGs, the magnitude of the real cost savings are probably not as high as estimated using traditional cost-assessment procedures. Though real customer cost savings come from the tax benefits available to POUs, the extent to which real cost savings can be achieved by IOUs depends on the ability of utilities to diversify the windpower financial risks away in ways not available to capital markets and NUGs. This diversification would decrease real financing costs by reducing the utility's marginal cost of capital below that available to NUG wind project owners. An assessment of the magnitude of these real financing benefits is beyond the scope of this paper, though Wiser (1997) identifies several possibilities.

VALUE OF THE FEDERAL PTC AND REPI

This section examines the federal PTC and REPI payments in more detail and evaluates their value in financing and economic analysis. Using the various cash-flow models, Table 3 shows cost estimates for all four ownership scenarios with and without the PTC and REPI. The POU cases are simply a replication of the results presented earlier. In the IOU and NUG scenarios, it is assumed that all investors have sufficient tax loads to absorb the full value of the tax credit.

TABLE 3. EFFECTS OF THE PTC AND REPI ON WINDPOWER COSTS

Ownership/Financing Scenario	Levelized Cost of Energy (¢/kWh)	
	With PTC or REPI	Without PTC or REPI
NUG Ownership, Project Financing	4.95	6.56
IOU Ownership, Corporate Financing	3.42	5.79
POU Ownership, Internal Financing	2.88	4.35
POU Ownership, Project Financing	3.43	4.89

As shown in the table, if the PTC and REPI were both discontinued, public ownership would, by far, be the lowest-cost development structure. IOU ownership, while still less costly than NUG development, would be substantially more costly than public ownership.

The federal PTC and REPI were, in part, enacted to stimulate domestic wind development, and were designed so that all owners of windplants would be treated more-or-less equally. The analysis presented in this paper and in other studies, however, demonstrates that these incentive schemes were not structured properly to meet this competitive neutrality objective.

First, as noted earlier, the REPI is subject to greater budget uncertainty than the PTC and is therefore often not even considered in project cost analysis. Second, to the extent that not all investors can absorb the full tax advantages afforded by the federal tax credit (i.e., do not have sufficient tax appetite or are limited by the alternative minimum tax), the value of the PTC is reduced (Wiser and Pickle 1997). Finally, secondary effects associated with receiving the PTC alter its value from the 1.5¢/kWh direct tax subsidy it was intended to provide. These effects include impacts on capital structure and the recursive tax benefits of obtaining the PTC (see Kahn 1995 and Wiser and Kahn 1996 for additional detail).

Wiser and Kahn (1996) conclude that the production incentive is most valuable to IOUs, which can easily absorb the full tax benefits of the PTC and are not affected by the capital structure impacts. NUG owners also receive substantial benefits from the PTC, but its value is reduced by alternative minimum tax restrictions and capital structure effects. Though the REPI is immune to the tax appetite and capital structure problems that arise with the PTC, it has been far less valuable than the PTC due to the budgetary uncertainty of the payments.

IMPACT OF TECHNOLOGY AND RESOURCE RISK: THE WIND FINANCING PREMIUM

A number of studies have alluded to the financing premium paid by renewable energy projects compared to other forms of electric generation (see, for example, Brown 1994; IRRRC 1991; Kahn 1995). Because of real and perceived technology and resource risks, NUG-owned wind projects typically receive financing that is both more costly and restrictive than that available to more traditional, gas-fired plants. While financial institutions have

become adept at evaluating natural gas supply and price risks, wind resource risks are less familiar. Windpower is also perceived as having high technology and performance risks.

This section quantitatively estimates the financing premium paid by NUG wind owners compared to traditional gas-fired NUG power plants. While the analysis presented here has no direct connection with the alternative ownership results of the previous section, the intention in this section is to: (1) estimate the magnitude of the cost savings available if windpower financing risks decrease to a level equivalent to current gas-fired facilities; and (2) evaluate the cost reduction potential of public policies designed to reduce the financial risks of wind projects.

The following financing variables are included in the analysis of wind and gas projects: (1) debt interest rate; (2) debt maturity; (3) minimum debt service coverage; and (4) equity cost. Table 4 lists typical differences between gas and wind financing terms (see Wiser and Kahn 1996 for details on these assumptions).

TABLE 4. NUG FINANCING INPUT COMPARISONS: WIND VS. GAS

Financing Variable	Windpower Project	Gas-Fired Project
Debt Interest Rate	9.5%	8%
Debt Maturity	12 years	15 years
Debt Service Coverage Ratio	1.4	1.25
Equity Cost	18%	12%

To estimate the financing premium paid by wind developers, the NUG windpower cash-flow model is run under two scenarios. The first applies the typical values for wind finance (the "base-case" shown earlier) and the second uses typical gas financing terms. All other inputs are equivalent. The results of the model runs are provided in Table 5.

TABLE 5. ESTIMATING THE WINDPOWER FINANCING PREMIUM

Windpower Financing Scenario	Levelized Cost of Energy (cents/kWh)	Percent Savings Compared to (1)
(1) Typical Windpower Project Financing Terms	4.95	na
(2) Gas Project Financing Terms	3.69	25%

The financing advantage afforded to gas-fired NUGs is clearly significant. If wind developers received similar financing terms and costs as gas-fired NUGs, the nominal levelized cost of windpower might decrease by 25% (1.3¢/kWh) compared to our base-case NUG ownership results. As wind turbine technology matures, resource evaluation becomes more accepted, and information becomes readily available to the financial community, debt and equity costs and terms may become less restrictive and costly for project financed wind facilities. These risks may never drop to a level equivalent to that of gas-fired power plants, but significant reductions in financing costs may be achieved. Additionally, there are a number of policy approaches that could be used to either directly reduce finance costs (e.g., government-subsidized financing) or indirectly reduce project risks by increasing revenues (e.g., auctioned production incentives, renewables portfolio standards, tax credits).

ELECTRIC INDUSTRY RESTRUCTURING

Because most of the results presented in this paper are linked to an industry structure in which utilities and private developers continue to invest in generating facilities as they have in the past, it is important to consider how electricity industry restructuring may change historic practices. This section first briefly discusses the impacts of restructuring on the alternative ownership results presented earlier and then describes the possible consequences of restructuring for NUG windpower development and finance.

With respect to the alternative ownership results, the primary concern under restructuring may be the viability of utility ownership for new windpower facilities. Indeed, restructuring has already slowed the pace of domestic wind development substantially and a number of U.S. utilities have abandoned or are attempting to renegotiate past commitments to own or purchase renewable energy. Yet, while the electric industry is moving away from regulated utility investment in new generation sources, the pace and outcome of industry restructuring will vary by state and utility, and the transition will not be seamless. Therefore, utility ownership of wind facilities to reduce costs is likely to remain a viable option for wind development in many areas of the country, especially in the near term and for POUs. It is important to note, however, that to the extent that restructuring results in improved utility cost-analysis techniques (i.e., techniques that more appropriately compare investment options with different risk profiles), utility project assessment procedures may no longer over-estimate the potential savings from direct ownership of renewables projects.

On a more general level, retail competition promises to fundamentally change the financing of NUG power projects. The long-term (20-30 year) power sales contracts that have traditionally facilitated project financing will become increasingly scarce. To attract project financing in the future, power developers are likely to require more equity, less debt, and shorter debt repayment periods. Developers will attempt to sign bilateral contracts with large end users, marketers, aggregators, and utilities, but contract terms are likely to be shorter than in the past. Financial hedging arrangements will also become increasingly common. Yet NUGs may find it impossible to secure contracts for all of their generation in advance. Therefore, an increasing focus on merchant plant development and on-balance-sheet financing is likely.

Although all NUGs will be faced with these new financing challenges, renewables may be particularly disadvantaged. First, renewables are often more costly than competing sources of generation and may therefore have difficulties financing projects based on anticipated future electricity prices. Second, given their capital-intensiveness, renewable are especially vulnerable to increased financing costs and shortened contract periods. Finally, many renewable energy companies may not be sufficiently capitalized to attempt corporate financing for large projects. Additional consolidation and fallout within the renewable energy industry can be expected.

While the decline of long-term contracts may make financing more difficult and costly for windpower developers, emerging markets for "green" power and/or the establishment of public policies designed to benefit renewables could create an investment climate in which windpower can flourish. It is therefore essential that the "green" power market be encouraged wherever possible and that new renewables policies be established to help alleviate anticipated financing difficulties and stimulate the development of an industry with important public benefits.

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TO FUTURE GENERATIONS

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ABSTRACT

First and Further Generations

One of the world's first 500 kW turbines was installed in the Netherlands in 1989. This forerunner of the current NedWind 500 kW range also represents the earliest predesign of the NedWind megawatt turbine. After the first turbines several design modifications followed, e.g. rotor diameter was increased and a tip brake was added. After that polyester blades were introduced and rotor diameter was further increased. The drive train was also redesigned. Improvements on the 500 kW turbine concept resulted in decreased cost and increased annual energy output.

The 500 kW turbines serve in the first Dutch off-shore wind farm installed in 1994. This pilot project established proof that off-shore implementation is a promising option for the Dutch energy supply. Installation of megawatt turbines off-shore is currently being studied.

Wind energy can substantially contribute to electricity supply. Maximum output in kilowatt-hours is the target.

INTRODUCTION

To keep abreast in the wind energy industry, a turbine manufacturer must continually dare to invest in development of new products.

NedWind, a Dutch pioneer in wind energy and a long established producer of wind turbines, has proven its capabilities in producing innovations more than once. The current product range includes the series NedWind 30 (250 kW), NedWind 40 (500 kW) and NedWind 50 (1,000 kW).

Developments since the first generation of the 500 kW Series has resulted not only in the world-wide installation of many wind farms including the first off shore wind farm in the Netherlands using 500 kW turbines, but also in the production of several 1,000 kW turbines.

NedWind further improved on earlier versions of 250 kW and 500 kW turbines, resulting in a range of types to fit a range of wind conditions.

NedWind turbines are fitted with two independent 'fail safe' braking systems, i.e., an aerodynamic brake effected by negative pitching of the blades and a mechanical brake of extraordinary high reliability.

Industrial computer systems control and protect the entire turbine. The newly developed NedWind Energy Control System (NECS) keeps track of all data generated during the life cycle of wind turbines. NECS handles remote servicing and monitoring as well as remote diagnosis, assuring prompt servicing and the lowest possible operational costs.

Integration of NECS into the general business process will prove to be an essential management tool, giving full insight in performance as well as financial aspects.

SUMMARY OF METHODOLOGY

NedWind constantly looks for ways to better the price performance ratio of its turbines.

Active Stall Control (ASC)

Maintenance of tip brakes in earlier turbine generations which had steel blades required cranes or other equipment. Furthermore, steel blades attracted lightning. Therefore NedWind began using polyester blades with full span pitch control. This was followed by the introduction of NedWind's Active Stall Control system (ASC) for the purpose of promoting design flexibility and power curve optimization.

All NedWind turbines feature ASC. The active negative pitching system combines the advantage of stall controlled behaviour in high winds with the means of accurately adjusting rotor power to the desired nominal value. Actively forced stall is very effective in regulating maximum power by eliminating damaging power spikes. Blade pitching is also used to optimize the power curve. Finally, negative pitching of the blades is applied as an aerodynamic brake.

In addition, ASC allows adjustments of the turbine characteristics to fit specific wind conditions at a site. If noise emission is to be attenuated, for example at night or in certain wind directions, blade pitch can be automatically adjusted for minimum noise production. Alternately, the blades can be pitched for maximum performance. Blade pitch can also be applied to allow turbine operation on heavily loaded grids.

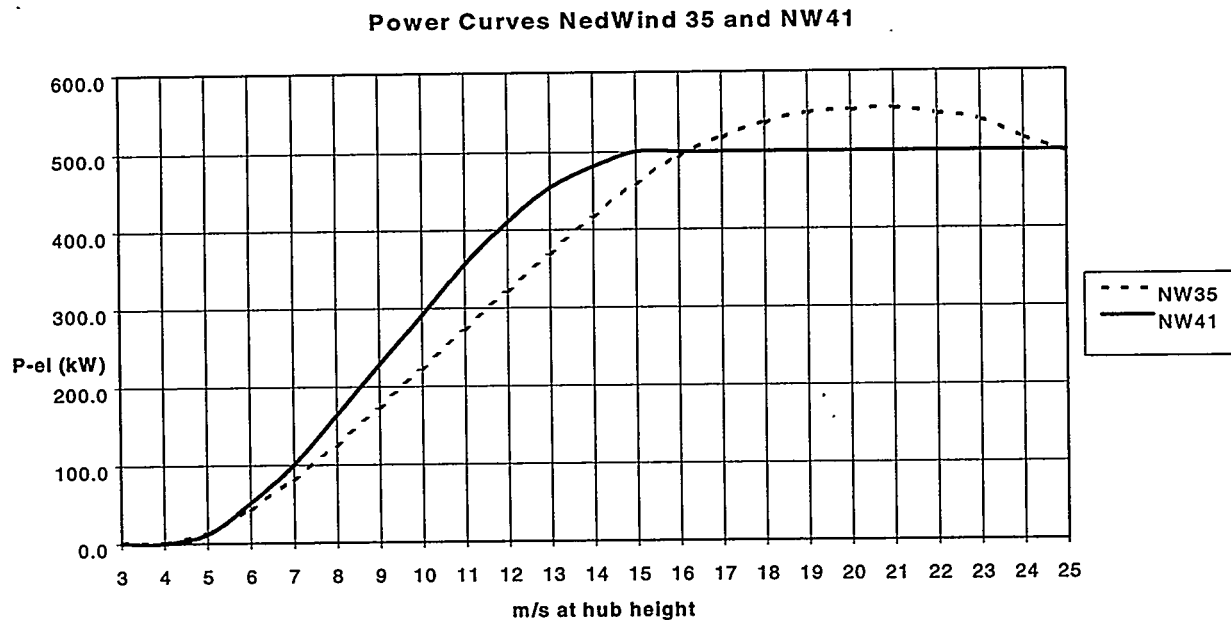


FIGURE 1 - COMPARISON OF POWER CURVES

Dual speed

Dual speed offers benefits for wind turbine operation in areas with low average wind speeds. In combination with Active Stall Control, dual speed turbines have several advantages over a single speed version.

- At a site with low average wind speeds, the power curve is optimized by switching at approx. 8 m/s to a lower level of generator power.
- Decreasing noise level, which is relevant especially in densely populated areas or at night time, is possible by operating at low rpm in low wind speeds. Whereas formerly a turbine had to be shut down in order to meet strict noise emission levels, noise can now be regulated by adjusting the blades for minimum noise production while maintaining maximum performance in the given conditions.

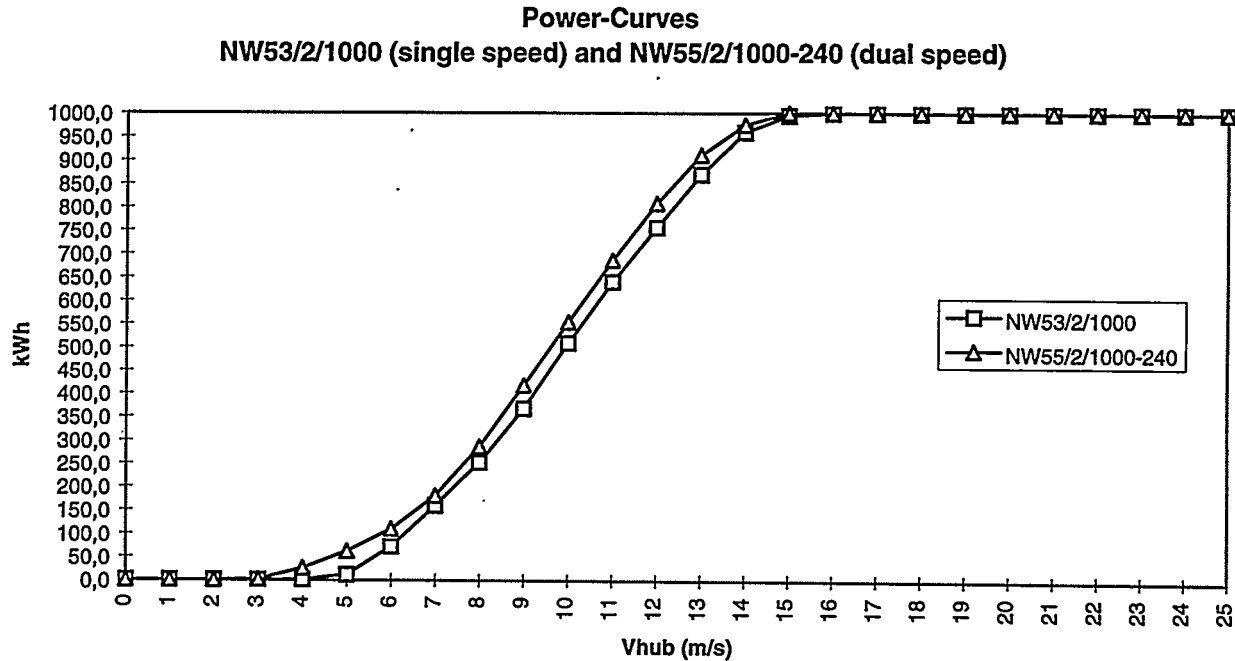


FIGURE 2 - COMPARISON OF POWER CURVE

Flexibility in design

In order to allow wind energy utilization in coastal areas as well as in regions with lower wind speeds, the design of rotor and tower can be varied to meet the requirements of a specific site.

Since the first generation of 500 kW turbines, the rotor diameter for NedWind's 500 kW units have increased from 35 up to over 40 meters.

The newest turbine in this class is a three bladed dual speed version with a rotor diameter of 46 meters. In the megawatt class rotor diameter increased to 55 meters. This has resulted in optimum performance of the turbines.

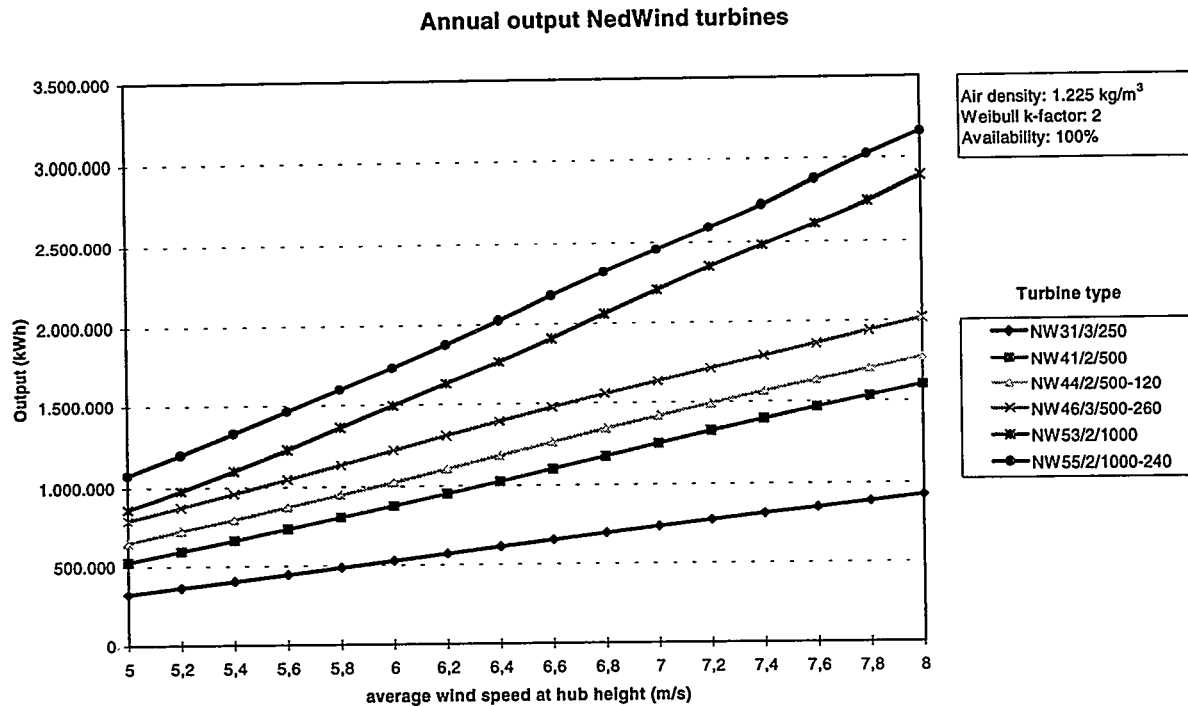


FIGURE 3 - COMPARISON OF ANNUAL OUTPUT

Extension and design improvement of turbine towers is another means to maximize output at a low average wind speed site. In the 500 kW turbine range, hub heights have increased from 39 to 50 to up to 65 meters. In the megawatt range heights have increased up to 70 meters.

Towers are dimensioned according to specific wind environments and wind speed classifications.

The difference in tower shape is influenced by the following requirements:

1. The design must withstand (heavy) buckling loading standards.
2. The tower must have a natural vibrational frequency which lies within the desired range.
3. The weight of the tower should be minimal.
4. The maximum allowable tower section length is 23 meters.

Requirements 1. and 3. are influenced by changing the shape of the tower. If the tower wall thickness is changed (to meet the buckling standard) the frequency of the tower will change. Tower stiffness is then adjusted to arrive at the proper natural vibrational frequency by choosing the shape.

A tower can be made more stiff when the "bottle shape" is chosen, and less stiff by choosing the "tapered/cylindrical" shape.

The design of a tower for specific wind regime is a continuing process in which several designs are considered after which a design which best fits the requirements, is chosen.

Yawing device

A unique device for yawing the turbines has been used in all of the NedWind 500 kW Series turbines. This device uses a high tensile steel cable and double action hydraulic cylinders. The steel cable is wound one and a half turns around a pulley fixed to the top flange of the tower. By pressurizing both cylinders in pulses the steel cable pulls the nacelle in one direction and runs back in the other. Signals from the wind

direction sensors, the manual controls and the untwisting process are translated into commands for the valves that activate the cylinders. Sensors in the yaw mechanism detect the total yaw angle.

The megawatt turbines do not feature the above described yawing device. Due to the larger dimensions of the turbines, yawing is accomplished by means of a yaw motor driven pinion engaged with a bull gear which is attached to the tower. The yaw motors are controlled by the wind turbine control system which translates signals from the wind direction sensors and the untwisting procedure into commands for the yaw system.

Modular Drive Train/Power Conversion System

NedWind applies one (or more) standard 250 kW generator(s) in its turbines, for the purpose of improving efficiency and power factor. At full power, all generators are grid connected. Depending on the power produced at a given time, one or more generators are connected to the grid. In this way generator efficiency is optimized.

RESULTS

Price Performance Ratio

NedWind has continuously improved turbine design and performance, which resulted in turbines which are low in both capital and maintenance costs. For instance, price performance ratios for the 500 kW class have decreased from PPR = 1 in 1989 to PPR = approx. 0.5 in 1997. It will not be long before wind turbines in general surpass fossil fuels both in terms of cost effectiveness and price.

TABLE 1 - PRICE PERFORMANCE RATIOS

Price Performance Ratio	wind class I	wind class II	wind class III
turbine type NW31/3 (250 kW)	0.37	0.44	-
turbine type NW41/2 (500 kW)	-	0.45	-
turbine type NW46/3 (500 kW)	-	-	0.50
turbine type NW53/2 (1,000 kW)	-	0.52	-

Flexibility

NedWind turbines are remarkable items of modern Dutch state-of-the-art innovative technology and are designed to make use of scarce sites for implementation of wind energy, on shore as well as off shore. Dimensioning of rotor diameters, towers and other components will further evolve with the focus on designing turbines to fit a specific wind regime.

Off-shore application

Some five years back wind turbines were relatively rigid generators, designed for application in a coastal wind climate and constructed in accordance to respective wind conditions and load spectra.

On inland sites performance of such wind turbines decreased, however application off-shore in the IJsselmeer proved feasible, with certain modifications to turbine construction and installation.

The first off-shore wind farm in the Netherlands with four NedWind 500 kW turbines as a pilot project has established proof that off-shore wind energy is a promising option for the Dutch energy supply and has given insight in the effect of this wind turbine project on its surrounding (water landscape, birds, fish).

The distance to the coast is 800 meters; the water depth is some 5 meters. The NedWind turbines were at that time the largest commercially available and were therefore chosen in order to achieve minimal operational costs.

Important factors in favour of implementing wind energy off-shore are:

- growing scarcity of suitable sites for wind energy on land;
- limited terrain roughness and unimpeded wind supply;
- less opposition with respect to visual impact of the turbines;
- length of licensing procedures.

The megawatt series

Important factors in favour of implementing megawatt scale turbines on land are:

- growing scarcity of suitable sites for wind energy;
- optimal utilization of a site with higher installed capacity;
- advantages relating to costs for infrastructure and grid connection.

In 1991 NedWind started the development of a megawatt turbine. Subsidies were granted by the European Committee and the NOVEM. Design and construction of the prototype in Spijk and the second turbine in Medemblik were covered by Thermie projects; the measurement program and verification of the Spijk turbine was covered by a Joule project.

The two-bladed megawatt NedWind 50 Series design, available in single or two speed version, meanwhile, consists of turbine types NW53 and NW55. Dimensioning of rotor diameter and hub height is adjusted to match the requirements of a specific wind environment.

Certification according to NEN6096/2: type NW53 - November 1994; type NW55 - March 1996.

Objectives of the measurement program for the prototype:

- Obtain detailed dynamic load and response data from a large stall regulated turbine.
- Evaluate the current design methods against measured data and hence to improve the predictive tools.
- Verify the NedWind 50 Series design.

Main conclusions of this measurement program are:

- An extensive measurement program has shown to be of major importance for verifying design models when upgrading turbine designs.
- Both noise and performance improvements could be achieved by optimized control strategy. Measured noise levels at Spijk: 102.9 dB(A) at high rpm and 90.4 dB(A) at low rpm.

- Optimizing of yawing procedure resulted in a higher performance.
- Measured blade loads are generally in reasonable agreement with the calculations. At higher wind speeds the dynamic loads are somewhat higher than predicted. Ongoing analysis of measurements will reveal more details.

The prototype of the NedWind megawatt turbine was installed in Spijk in February 1994. The Spijk turbine has a rotor diameter of 52.6 meters and a hub height of 40.7 meters. These dimensions negatively influenced the aesthetic value and in the installation of later turbines this fact was taken into consideration.

The prototype was tested as a dual speed turbine, consisting of 6 generators of which 2 were operated in lower wind speeds respectively at lower rpm. In current megawatt turbine types of the dual speed version 4 double wound generators are implemented.

Results of the measurement program on the Spijk turbine convinced NedWind of the feasibility of the megawatt turbine and the NW53 turbine type became commercially available. Design of the turbine is basically similar to that of the 500 kW series. The modular drive train, Active Stall Control and dual speed are comparable. However, in view of the weight of the nacelle, yawing by means of steel cables as is done by medium-sized turbines proved to be cumbersome and this system was substituted for a yawing device with a gear ring and two yaw motors.

The world's first megawatt turbine to be commercially operated, situated at Medemblik, was installed in May 1995 at the same spot as the NEWECS-45 experimental 1,000 kW turbine was erected at the end of 1985. In April 1995 the old turbine was taken down and the 60 meter tower was shortened to 53 meters. The new megawatt turbine was then mounted on the existing tower on May 23. Annual output is estimated to be approx. 2.3 million kWh. Annual output in 1996 was 2.2 million kWh whereas Windex 1996 = 90%.

The now proven megawatt technology resulted in the development of turbine type NW55, which dimensioning is fit for implementation on inland sites. The rotor diameter is 55 meters, hub height is 70 meters. At the time other competitors are installing megawatt turbines in a prototype phase against high R&D costs, NedWind is already producing in batches.

The first windfarm featuring megawatt turbines in the Netherlands is situated in Moerdijk on an industrial location along the Hollands Diep waterway. The Moerdijk wind farm was realized as a turn-key project and became operational in May 1996. NedWind served as a contractor for the whole project and acted on behalf of a private investor who expressed explicit belief in the future of wind energy.

The wind farm is situated in an eco-industrial environment, in the neighbourhood of the Shell petrochemical plant. In this industrial area various ways of generating power are employed. It contains the wind farm, a waste incineration plant as well as a combined heat and power station. The waste incineration plant generates electricity by means of steam and gas. Steam is supplied to Shell and electricity to the grid.

The wind turbines are placed on the premises of an environmental friendly wood processing company and of the adjacent waste incineration plant. The soil is of the typically Dutch soft structure. The foundation blocks are over 12 meters in diameter. Each foundation rests on 15 piles of lengths up to 30 meters. The turbines are heavy weights of some 1,000 tons from the pilings in the ground to the wind vane on the nacelle. When a blade is in vertical position, it reaches up to 100 meters high. The crane applied to mount the nacelle has a hoisting capacity of 800 tons.

In March 1996, the sales price for the complete installation (up to and including grid connection) of this wind farm was NLG 2,162,500 per turbine (some US\$ 1,138,158 each), whereas investigations at the end of 1996 show prices of some US\$ 1,000,000 as most cost effective options to install one MW of wind capacity with turbines in the 500/600 kW range. Comparing the Moerdijk wind turbines to the standard going rate of US\$ 1,000 per kW, a difference of approx. 14% made turn-key realization at this specific site with its specific characteristics possible.

Based on the predicted wind speed at the Moerdijk site, the turbines are expected to produce a maximum of 1,850,000 kWh per annum. On May 12, 1997, being 10 months after commissioning, the meter shows an output of 1,700,000 kWh (including the test period), whereas Windex over the whole year 1996 was 90%. There proved to be periods of 24 hours during which the Moerdijk megawatt turbines showed an output of 24,000 kWh.

At the Moerdijk turbines with a hub height of 70 meters a sound emission value of 104 dB(A) at high speed rpm and 94 dB(A) at low speed rpm was measured by independent organizations DEWI and LBP and was approved by local authorities in a critical densely populated environment of Holland.

For future production of the MW turbines a few more changes are made. Yawing system is adapted and once more ameliorated. Rotor diameter of 55 meters is reached with a newly designed rotor blade instead of implementing spacers.

Future applications

Building wind turbines on water is more expensive than a comparable project on land, primarily due to costs for foundations, grid connection, hoisting and security measurements for shipping.

After building the first off-shore project in the Netherlands, the project at that time proved to be some 30% higher in cost as compared to an identical windfarm constructed on land.

Since output and performance of modern wind turbines are steadily increasing, expectations are that an off-shore project consisting of several larger turbines can operate even more cost efficiently. Optimizing support structure design, turbine and wind farm size and hub height leaves room for cost reduction. Cost price can be reduced, e.g. by implementing a universal generic foundation and tower design, less complex towers and less provisions with respect to noise emission.

Studies are undertaken to determine the potential of wind farms off-shore, be it either close to the Dutch coast or far out at sea. Or even in windy regions in neighbouring foreign countries like Scotland, Norway or the Shetland Islands. The wind energy potential in the latter areas is substantial (hundreds of gigawatts) in view of the respective wind speeds of 8.3, 7.7 and 10.5 m/s in average. However, technically this option will have to cope with the problem of the High Voltage Direct Current transmission cables which will have to convey electrical power over distances ranging from 650 to 1,200 km and up till now cannot transmit more than 600 MW. However, cables with capacities of 1 gigawatts are expected to be developed in due course. In any case a transmission loss of 12% should be reckoned with.

In the Netherlands itself the potential of semi-off-shore sites like sand banks or in shallow water along the coast could represent 2,800 MW in total. Feasibility of a 100 MW pilot project near shore, to be realised within 2 to 5 years, is being studied under the auspices of the NOVEM.

The most futuristic option in the long run is implementation of wind energy some 30 to 100 km to the north of Holland, outside of the oil rigging areas and shipping routes. Within a surface of 750 square km

some 8,000 MW of capacity could be feasible, for instance the installation of several wind turbines on one platform, constituting a total capacity of several MW.

Research will have to be done with respect to e.g. foundations in environments with waves of some 10 meters high and water depths of some 10 to 40 meters. Also the technical limits to turbine capacities will have to be investigated. Last but not least turbine construction will have to be adapted with respect to aggressive environmental influences like saline air and extreme fatigue factors.

Alternative plans for oil rig disposal

In 1996 Shell issued a competition in which industries were invited to submit plans for disposal or reuse of the oil platform Brent Spar. A Dutch consortium put forward an imaginative plan to transform the disposal of the Brent Spar platform from an environmental problem into an environmental asset and simultaneously accelerate the development of renewable energy systems. NedWind has contributed extensively to the wind energy part of the plan.

Although this alternative was not accepted by Shell in the end, it gives much to reflect upon.

The revolutionary concept originated from the desks of a group of companies with expertise in the field of construction, structural engineering, wind and wave power, electricity generation and distribution and environmental management.

The proposal was to create an eco-friendly floating power station by refurbishing the topside structure and equipping it with three NedWind megawatt wind turbines. Implementation of megawatt-scale turbines implies optimal utilization of a site.

The plan was to have the base structure of Brent Spar towed to a new location off the west coast of Scotland where it would be rejoined to the refurbished topside. The next stage would have been the installation of the initial set of wave power units, with a capacity of 0.7 MW. The whole structure would have been connected to the grid by means of a power line to the shore. The number of wave power units would gradually have been increased until the power capacity of the whole structure would have reached 19 MW.

The new method would have been subject to further intensive studies. It might have proved to be the ideal solution for other off-shore structures like the Brent Spar.

CONCLUSIONS

Wind energy is a renewable source and can substantially contribute to the supply of electricity. Installation of wind farms require a short time period compared to the installation of traditional power plants. Generating electrical power by means of wind energy has no harmful effect on the environment because the emission of toxic substances, which contribute to global warming and acid rain, are avoided. It is thus critical that use of wind energy is further expanded and in order to do so a low price performance ratio is important for wind energy to be able to successfully compete with fossil fuels. Maximum output in kilowatt hours is also important. This can be accomplished by optimizing turbine performance to a specific wind zone. During the past five years, the wind energy industry trend has been to improve on the output of a turbine by increasing turbine size. NedWind is also engaged in increasing turbine size. Further improvement of the existing technology and using flexible components may well prove to be a way to increase energy output and cost effectiveness in both medium and large size wind turbines.

LIGHTNING HAZARD REDUCTION AT WIND FARMS.

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1. Abstract.

The USA wind farm industry (WFI) largely is centered in low-lightning areas of the State of California. While some evidence of lightning incidents is reported here, the problem is not regarded as serious by most participants. The USA WFI now is moving eastward, into higher areas of lightning activity (1).

The European WFI has had many years experience with lightning problems. One 1995 German study estimated that 80% of wind turbine insurance claims paid for damage compensation were caused by lightning strikes (2).

The European and USA WFI have not adopted site criteria, design fundamentals, or certification techniques aimed at lightning safety. Sufficient evidence about lightning at wind farms is available to confirm that serious potential problems exist (3).

Lightning current parameter	Relevant component of the lightning strike	Effect	Endangered components
peak current I	first impulse current	potential rise of the wind power plant, voltage drop across cable shields	nacelle & power plant building, SCADA
specific energy W/R	first impulse current	electromechanics, heating, evaporation	blades and bearings stressed by I
charge Q	long duration currents, first impulse current	melting	blades and bearings
average current steepness $I/T1$	subsequent and super-imposed impulse currents	magnetic induction	SCADA
number of impulse currents n	subsequent and super-imposed impulse currents	repeated H-field impulses	SCADA

Fig. 1. Lightning Effects to components of a wind power plant (4).

P. 2, wind farms

2. Recent Case Studies.

2.1 USA Experience.

2.1.1 At one southwestern USA Wind Farm lightning damage exceeded \$50,000 in the first year of operation. Damage occurred to blades, generator, controller, control cables, SCADA, etc. A lightning protection retrofit program by manufacturer included air terminals, TVSS products and additional bonding & grounding measures. Further lightning damage occurred after the retrofit. A consulting engineering specialist in lightning mitigation was hired. Recommendations for enhanced grounding measures are being implemented. TVSS, air terminal, shielding, nacelle, blade treatment, and personnel safety recommendations have not been implemented at this time. (5)

2.2 Eighty-five percent of the downtime experienced by a second southwestern USA commercial wind farm was lightning-related during the startup period and into its first full year of operation. Direct equipment costs were some \$55,000, with total lightning-related costs totaling more than \$250,000. (6)

2.2 European Experience.

2.2.1 A 1996 European retrospective study was conducted of some 11,605 wind turbine years experience in Denmark and Germany. Very accurate operational records were available for analysis. General findings indicated:

2.2.1.1 Lightning faults caused more loss in wind turbine availability and production than the average fault;

2.2.1.2 Ranking in descending susceptibility to lightning damage were turbine control systems, electrical systems, blades, and generators;

2.2.1.3 The number of failures due to lightning increases with tower height;

2.2.1.4 Wood epoxy blades have significantly less damage rates than GRP/glass epoxy blades. (7)

2.2.2 The German electric power company *Energieerzeugungswerke Helgoland GmbH* shut down and dismantled their Helgoland Island wind power plant after being denied insurance against further lightning losses. They had been in operation three years and suffered in excess of 800,000 German Marks damage. (8)

3. Codes, Designs and Testing.

Many USA lightning codes and standards are incomplete, superficial, and provide more benefit to commercial vendors than to those seeking relief from lightning's effects. Protection devices that claim to offer absolute protection abound in the marketplace, confusing specifying architects, engineers, and facility managers. Safety should be the prevailing directive.

P. 3, wind farms

The time to review possible lightning effects upon wind turbines is during the site selection and design stages. A lightning mitigation plan can be derived from a systematic hazard analysis. A testing and verification program can provide validation and certification that the protective measures will function as engineered. Frequently, lightning problems do not receive consideration during the design stage. It then requires a specialized lightning safety engineer to analyze the effects of lightning during operations, and provide a rationale for "safety-through-redesign" modifications to the wind farm facilities. Adding lightning safety measures under retrofit circumstances frequently is awkward and expensive.

4. Conclusion.

Lightning prevention or protection, in an absolute sense, may be impossible. However, hazard mitigation and threat reduction are achievable through an understanding of the lightning phenomenon and preparation for its effects. Adoption of a Lightning Safety Guidelines document provides a rational and systematic approach toward lightning safety. The general outline of such a program should include:

1. Management Approval.
2. Personnel Training.
3. Site Analysis.
4. Threat Warning.
5. Safety Devices—air terminals, bonding, shielding, grounding, transient voltage surge suppression, etc.
6. Testing/Certification/Maintenance.

The typical cost for a comprehensive lightning mitigation hardware system for wind farms is some 0.50 - 0.80 percent of total capital costs. One time costs for major component failure due to lightning easily can exceed this figure.

Wind industry participants should develop a comprehensive lightning safety document (9). When applied with an understanding of lightning behavior, it will enable manufacturers and operators to have working criteria to apply to most any wind turbine design or location.

P. 4, wind farms

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**NATIONAL RENEWABLE ENERGY LABORATORY
PROGRAM ON LIGHTNING RISK AND
WIND TURBINE GENERATOR PROTECTION**

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1.0 INTRODUCTION

In the early development of wind turbine generators (WTG) in the United States, wind farms were primarily located in California where lightning activity is the lowest in the United States. As such, lightning protection for wind turbines was not considered to be a major issue for designers or wind farm operators. However, wind turbine installations are expanding into the Midwest, Southwest and other regions of the United States where lightning activity is significantly more intense and lightning damage to wind turbines is more common. There is a growing need, therefore, to better understand lightning activity on wind farms and to improve wind turbine lightning protection systems.

In support of the U.S. Department of Energy/Electric Power Research Institute (DOE/EPRI) Utility Wind Turbine Verification Program (TVP), the National Renewable Energy Laboratory (NREL) has recently begun to take steps to determine the extent of damage due to lightning and the effectiveness of various lightning protection techniques for wind power plants. Working through the TVP program, NREL will also perform outreach and education to

- help manufacturers to provide equipment that is adequately designed to survive lightning
- make sure that operators are aware of effective safety procedures
- help site designers and wind farm developers take the risk of lightning into account as effectively as possible.

This paper will describe the NREL program for addressing lightning protection for wind turbines. A test program will begin this summer at the Central and South West Services Inc. (CSW) wind farm near Fort Davis, Texas, to assess lightning risk, the frequency of lightning strikes on wind turbines compared to risk assessment predictions, and the effectiveness of some protection techniques. A Web page will be assembled to provide resources for designers and operators and feedback for issues as they arise. Also, a database of lightning events (and corresponding damage) will be collected to assist in maturing the understanding of wind turbine lightning protection.

2.0 DESCRIPTION OF PROBLEM

Wind turbines are tall structures, and they are often located atop hills in cleared or naturally open areas. Consequently, they are highly exposed to direct lightning strikes. Additionally, WTGs are controlled by sophisticated low voltage controllers, and they are usually connected by distributed monitoring systems. Such systems are at extreme risk of damage from indirect lightning effects due to the nature of the associated high current pulses.

Hundreds of damaging lightning events on WTGs have been reported throughout the U.S. and Europe. The damage has varied from direct strikes to blades and electrical generation/transmission systems to indirect damage in wind farm monitoring communications circuits. The downtime and repair costs from these events has been large, according to a 1994 survey and article in *Windstats* (1), an analysis of survey data by UMIST (2), and reports from some projects in Texas (3). In many cases, even minor damage can lead to extended downtime and loss of production due to the difficulty of identifying, repairing or replacing controller components. In fact, the UMIST report indicated that a lightning fault causes more loss in wind turbine availability and production per incident than most other faults.

2.1 DAMAGE MECHANISMS

Dodd et al. (4) indicate that there are two mechanisms by which lightning strokes affect wind turbine operation:

1. Loss of hardware
 - mechanical hardware such as blades, bearings, etc.
 - high-voltage equipment such as generators, transformers, contactors, and switch gear
 - low-voltage circuits such as data acquisition, communication lines, and controller boards.
2. Loss of operation
 - damage on any hardware component listed above may cause loss of operation, which eventually translates to higher cost of wind-generated energy.

Mechanical hardware damage is usually caused by directly conducted lightning currents. Damage is minimized by installing lightning protection on each individual component. Heat related damage is caused by I^2R losses caused by the lightning current flowing through highly resistive material, e.g., blade FRP material. Thus, in this case, components prone to direct lightning current conduction should be protected by providing an alternate current path to deflect the majority of the lightning current from flowing through the component.

Electrical hardware damage can be caused by voltage surges due to inductive or capacitive coupling, so-called indirect effects of the lightning currents. Voltage surges can also be conducted through wires from inside or outside the wind farm. Surge protection and proper shielding can increase the immunity of electrical hardware against such disturbance, thereby minimizing the damage on the electrical side.

2.2 CURRENT STANDARDS AND RESEARCH

As is common in the wind industry, current IEEE standards (5, 6) and other structural protection standards (7) fall short in comprehensively covering the wind turbine application. Essentially, a WTG is a power plant atop a lightning rod with a low voltage controller between it and the path to ground. There is also a

(usually) non-conductive, expensive component as the highest point, the blades. The problem is compounded by the stochastic nature of lightning. It is difficult to make judgments on patterns of damage when the nature of the event (and the protection system) can vary significantly.

International interest to improve WTG lightning protection was strongly displayed at well-attended experts meetings in 1994 in Milan, Italy (8) and recently in Germany. These were sponsored by the International Energy Agency (IEA) under their Annex XI Cooperation of Wind Turbine R&D. A great deal of interesting research on lightning protection in Europe was reported, including evaluating lightning connection points, testing blade and turbine protection techniques, and damage forensics. During the first meeting, it was decided that the IEA should develop recommended lightning safety practices to protect a wind turbine and make them available to the wind industry. NREL engineers attended both meetings and are currently participate in the development of the IEA recommended practices.

3.0 NREL LIGHTNING PROTECTION PROGRAM

In response to these issues, NREL has instituted a program to address the gaps in lightning protection practices in the wind industry. The goals of this effort are as follows:

- assist U.S. wind industry (utilities, turbine manufacturers, developers, O&M organizations) in protecting the wind turbines and wind farm equipment from lightning and its impacts
- maximize the safety of wind farm personnel
- minimize downtime of wind turbine operations due to lightning
- minimize wind turbine component damage that may occur due to lightning strikes
- identify reliable diagnostic procedures for accurately identifying that observed damage was caused by lightning.

NREL hosted a wind turbine lightning protection meeting at the National Wind Technology Center (NWTC) in January 1997 as part of its role to provide technical support to the Utility Wind Turbine Verification Program, a collaborative effort between the Department of Energy and the Electric Power Research Institute. Meeting participants included representatives from EPRI, utilities, wind turbine manufacturers, wind farm operators, and consultants specializing in wind energy and lightning protection. Information was shared about operational experiences with wind turbines in high lightning risk areas, recommended lightning protection techniques and design practices, and other related issues. At the close of the meeting, the participants recommended that NREL pursue the following lightning research activities:

- survey the existing lightning protection systems at a selected wind farm, monitor the lightning activity, and document the resulting damage
- develop a Web page for WTG lightning protection to inform the wind industry about lightning-related issues and experiences
- publish a technical report and present technical papers at industry conferences and workshops to disseminate lightning information gathered
- develop guidelines for WTG and wind plant lightning protection that complement the IEA recommended practices.

These and other steps are being taken to further the understanding of lightning protection of wind turbines.

3.1 SITE LIGHTNING RISK EVALUATION

The first item to be addressed is the assessment of lightning risk for specific WTGs at a potential wind farm site. We will utilize various methods that predict this risk level, and in-field monitoring data will be used to evaluate these techniques. Additionally, site personnel safety will be assessed using advanced

lightning warning systems that provide sufficient notice to allow personnel to move to safety in advance of a lightning storm with minimal false alarms.

The National Lightning Detection Network (NLDN) will be used to perform site evaluations for existing wind farms. This will be matched against the standard approach and information from the in-field test. Although the NLDN has a smaller data history (8 years) than the isokeraunic map approach (100 years), it may prove to be more useful due to its accurate and localized nature.

Advanced warning of lightning is very useful for wind farm operations and maintenance (O&M). It allows operators to have warning of incoming storm activity with sufficient time to evacuate technicians from the usually exposed wind farm areas and the dangerous proximity of the turbines (due to the risk of deadly step voltages). Such devices range from the extremely sophisticated optical and potential gradient devices to simple hand held units that sense characteristic electromagnetic pulses from lightning strokes. This hardware will be deployed on-site and exercised and evaluated by O&M personnel and the test engineers.

3.2 FIELD TEST

A test is currently being instituted by NREL to determine the effectiveness of various lightning protection techniques for wind power plants. Analysis will be carried out to assess site specific lightning risk, the frequency of lightning strikes on wind turbines compared to risk assessment predictions, and the effectiveness of some protection techniques.

Additionally, the test includes evaluation of site lightning risk assessment tools and on-site lightning alert equipment to provide for operator safety. Such equipment provides a warning when a lightning storm or high-risk conditions are incoming so that operations and maintenance personnel or visitors can suspend activity and move to safety. It may also prove possible to use information from these devices to disconnect selected electrical or communications circuits during the time that lightning is in the area of the wind farm.

All twelve of the Zond Z-40 wind turbines at the CSW site and the point of common coupling (PCC) with the 25 kV distribution line will be instrumented to determine the source of lightning strikes. Sensors on each turbine will be set to monitor the lightning strikes. The lightning current will be detected with inductive shunts and current sensors (items 1 and 2 in Figure 1), and the communication lines will be monitored for voltage surges. These sensors and a pair of lightning-activated video cameras will be used to identify strike locations (i.e., what turbine, where on the turbine, or where on the ground nearby a turbine) and time stamp any lightning events. The point of common coupling (PCC) at the junction between the wind farm and the utility will also be monitored to capture and identify surges from either inside the wind farm or from the external power distribution network.

The National Lightning Detection Network will be utilized to evaluate the strength and the nature of strikes to WTGs and the wind farm site using the collected time stamped data. It is expected that we can measure the level of disturbance captured by the sensors on the wind turbines and the PCC and correlate the data from NLDN to gauge the level of lightning damage immunity of the wind turbine system.

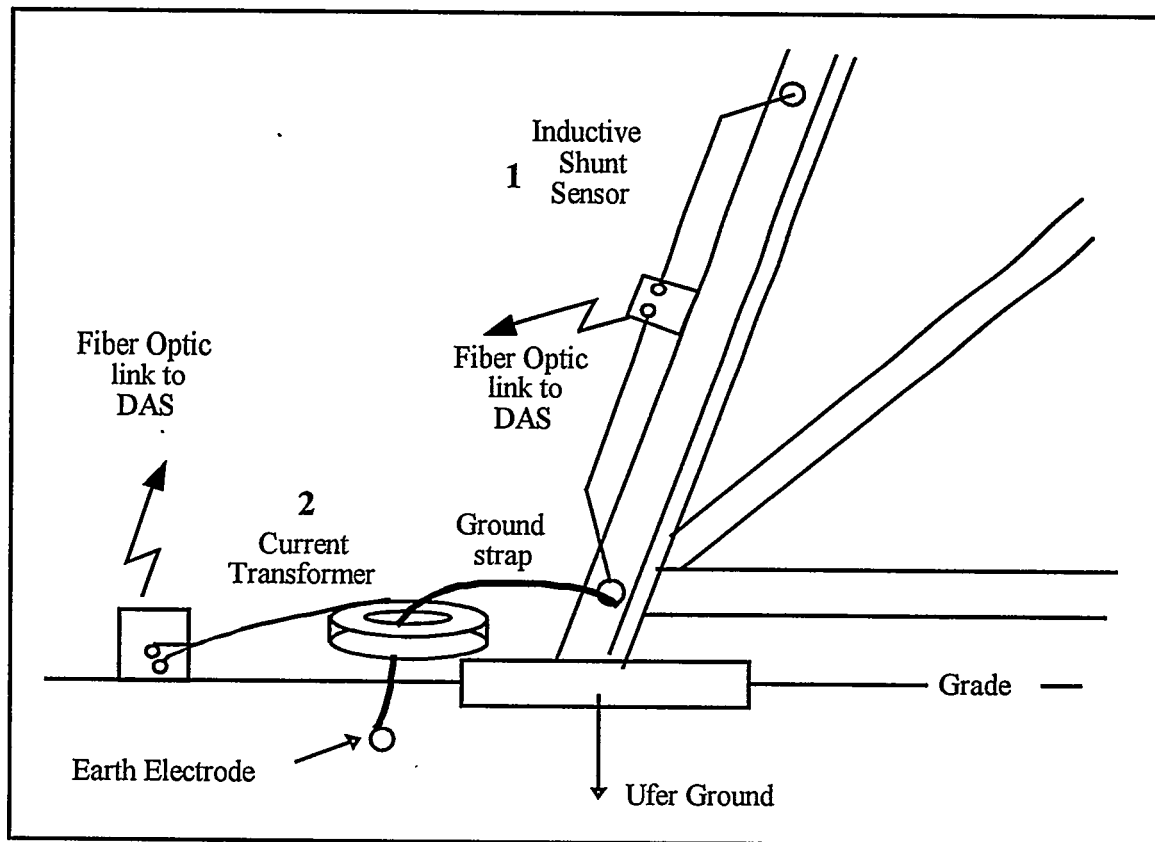


FIGURE 1 TOWER LEG LIGHTNING CURRENT SENSORS

3.3 INFORMATION DISSEMINATION

The Web page will be the primary vehicle for distributing information gathered from testing and monitoring other research. We expect to keep abreast of international research and recommendations through participation in the IEA program and basic literature searches. Additionally, several lightning consultants will be included to advise on proper protection techniques as reflected by research in complementary fields such as utility systems, aircraft, and the like.

The proposed contents of the Web page follows:

- NREL background on lightning protection for WTG & bibliography
- technical papers and reports on lightning relevant standards and recommended practices from IEA, IEEE, or NEC
- NREL lightning research activities—current status & future plans
- lightning damage survey for wind farm operators (i.e., forms, database statistics and results)
- lightning protection project results and recommendations (as they become available)
- wind turbine lightning safety guidelines for site personnel.

It should be noted that the information available and the survey data presented in the Web page will be masked in order to provide anonymity to the manufacturer and/or operator. This data will be gathered into a database and analyzed for the purpose of furthering our understanding of the impact of lightning damage to better protect wind turbine operation.

4.0 SUMMARY

In support of the DOE/EPRI TVP, NREL has begun to take steps to determine the extent of damage due to lightning and the effectiveness of various lightning protection techniques for wind power plants. Working through the TVP program, NREL will also perform outreach and education to

- help manufacturers to provide equipment that is adequately designed to survive lightning
- make sure that operators are aware of effective safety procedures
- help site designers and wind farm developers take the risk of lightning into account as effectively as possible.

A test program will begin this summer at a Texas site in order to assess lightning risk, the frequency of lightning strikes on wind turbines compared to risk assessment predictions, and the effectiveness of some protection techniques. A Web page will be assembled to provide resources for designers and operators and feedback for issues as they arise. Also, a database of lightning events (and corresponding damage) will be collected to assist in maturing the understanding of wind turbine lightning protection.

ACKNOWLEDGEMENTS

This work was performed under DOE Contract No. DE-AC36-83CH10093 and NREL Subcontract No. TAM-7-17215-01. Help was provided by Sandy Butterfield, Brian Smith, and Niels LaWhite. Support was provided by the following participants: EPRI (Edward DeMeo, Chuck McGowin), CS&W (Brian Champion), Zond (Kevin Cousineau), Global Energy Concepts (Karen Conover), Earl Davis, National Lightning Safety Institute (Rich Kithil), Lightning Protection Corp. (Chester Kawieki), University of Florida (Prof. Martin Uman), Southwestern Public Service (Stephen Jones), LG&E (Jeff Holbrook), Green Mountain Power (John Zimmerman, John Saint Cross), Wisconsin Power Co. (Jayme vanCampenhout), Lightning Technology Inc. (Andrew Plummer)

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ATMOSPHERIC TESTING OF WIND TURBINE TRAILING EDGE AERODYNAMIC BRAKES

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ABSTRACT

An experimental investigation was conducted using an instrumented horizontal-axis wind turbine that incorporated variable span trailing-edge aerodynamic brakes. A primary goal was to directly compare study results with (infinite-span) wind tunnel data and to provide information on how to account for device span effects during turbine design or analysis. Comprehensive measurements were utilized to define effective changes in the aerodynamic coefficients, as a function of angle of attack and control deflection, for three device spans and configurations. Differences in the lift and drag behavior are most pronounced near stall and for device spans of less than 15%. Drag performance is affected only minimally (<70%) for 15% or larger span devices. Interestingly, aerodynamic controls with characteristic vents or openings appear most affected by span reductions and three-dimensional flow.

INTRODUCTION

Mechanical brakes are common components on many wind turbines. These brakes are effective at holding a stopped rotor and in most cases at slowing a turning rotor. However, mechanical brakes may prove inadequate or worst yet they may fail under severe wind conditions or with a loss of generator load. An additional or redundant means of governing the rotor rotation speed is desirable.

Trailing-edge aerodynamic control surfaces, mounted near the rotor blade tips, offer a direct and powerful means for regulating rotor torque. These control surfaces or devices are sometimes referred to as "ailerons," due to their rough resemblance to similar controls on an airplane. However, their function is to adjust the aerodynamic loads over the primary torque producing area of a wind turbine blade. To be effective in this application the control device must adjust the airfoil's flow character so as to reduce or even reverse the normal pro-rotational torque of the entire rotor. This requirement for turbine braking is demanding, especially in light of the turbine's inherent function of generating high torque during typical power generation periods.

A great deal of investigation has been undertaken over recent years to develop, evaluate, and employ aerodynamic control devices principally for rotor braking. Power modulation and active control (or load alleviation) are quickly emerging as additional high priority applications. A number of different configurations have been evaluated in wind tunnel tests and comprehensive data bases for each are available to designers^{1,2,3,4,5,6,7}. Nevertheless, there have been questions raised regarding the utility and accuracy of the wind tunnel data. Most significantly, the information has been almost exclusively for

infinite-span devices. Turbine designers need more representative aerodynamic information or they need to better understand how to apply the existing data.

An investigation was undertaken to evaluate aerodynamic control devices, for turbine braking applications, in a more realistic environment. A rotor was modified to incorporate aerodynamic control devices and tested on a instrumented full-scale turbine at the National Renewable Energy Laboratory's (NREL's) National Wind Technology Center (NWTC). Three device configurations, each of variable span, were evaluated. Blade loads and turbine conditions were measured and used to identify the aerodynamic performance increment of each device in a rotating, unsteady, and three-dimensional environment. The resulting data are compared to infinite-span data obtained from similar wind tunnel tests. The reader is referred to another publication, by Miller, Quandt, and Huang, for a much more detailed account of the atmospheric tests and results. Extensive aerodynamic data, including device hinge moments, is included in this soon to be published NREL report.⁸

EXPERIMENTAL APPARATUS AND METHODS

The atmospheric test was performed using the NWTC's Grumman 20kW horizontal-axis wind turbine previously labeled and commonly known as the Combined Experiment Rotor.⁹ This turbine utilized rectangular planform untwisted blades of the 5.0-meter span, 0.46-meter chord, and a constant S809 airfoil profile from root to tip.

Test blades were modified at the Wichita State University (WSU) National Institute for Aviation Research (NIAR) research machine shop. The outboard trailing-edge of each fiberglass blade was cut out for device installation and the spars were reinforced. Provisions for three different device spans were included. Each device, with a span of 7.5%, could be deflected independently or together with the others, thus allowing a number of combinations for evaluation (see Figure 1). Device leading-edge and cove pieces were changed out and the hinge points were moved in order to generate specific aerodynamic configurations.

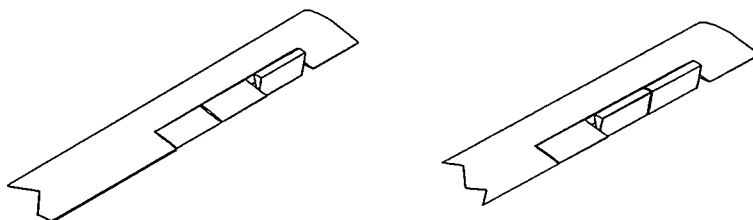


FIGURE 1 DIAGRAMS ILLUSTRATING DEVICES OF DIFFERENT SPAN.

Figure 2 shows a schematic diagram of the forty percent chord Spoiler-Flap, Vented Aileron, and Unvented Aileron device configurations examined in the investigation. The Spoiler-Flap and Vented Aileron utilize the same pivot point (located on the chordline, at 80% chord). The Unvented Aileron control surface pivoted about a point next to the surface (at 60% chord). Note that the Spoiler-Flap trailing-edge is designed to move primarily downward, whereas the other two configurations are designed to move trailing-edge up. Small deflections in the other directions are possible for power modulation applications.

As was mentioned previously, the test turbine was fully instrumented. Blade resultant edgewise and flap bending moments were measured by strain-gages mounted at the root end, near the hub. Position encoders recorded blade pitch, as set by the operator, and turbine yaw angles. An array of atmospheric sensors measured air velocity, pressure, and temperature at the site. The rotor rotation speed (nominally 72 RPM) was also monitored and measured. Signals from the various sensors were transmitted to a computer-based

data acquisition system for real-time display and recording. Calibration data, obtained just prior to tests, were applied so that final measurements were accurate and in the appropriate engineering units. The data acquisition system made approximately 512 measurements per sensor, per second, for a total of thirty rotor revolutions.

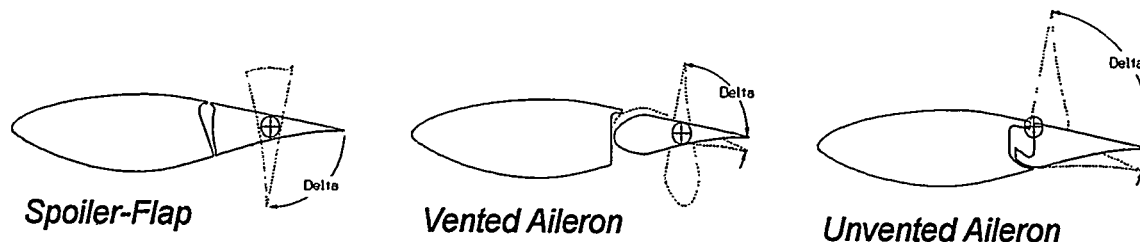


FIGURE 2 THE 40% CHORD AERODYNAMIC DEVICES EXAMINED, AS INSTALLED ON A S809 AIRFOIL.

Wind speeds of 1.0-5.0 meters per second (≈ 2.0 -8.0 mph) were expected during the scheduled test period (i.e., summer) at the NWTC. Sustained and reasonable data acquisition rates for a turbine in this condition seemed unlikely. As a result, it was planned to operate the machine in a "motored" configuration. Preliminary calculations, using the PROP 93 turbine performance prediction code,¹⁰ indicated that it would take too much time for the wake of a three-bladed rotor to convect downstream at the anticipated wind speeds. Thus, to minimize the possibility of significant wake interactions, a one-bladed rotor with counterweights was used. Flow visualization experiments verified that the blade wake would indeed convect downstream, as desired, as long as wind speeds were above approximately 2.0 meters per second (≈ 4.0 mph).

Once the turbine was prepared, testing began. In summary, a particular device configuration was set up, the motor was turned on, the blade pitch was swept through the desired range, and data were recorded. Eleven blade pitch settings and five device deflection angles were examined for each device span and configuration. The test Reynolds Number (R_δ), based on the blade chord, a fixed rotor rotational speed of 72 rpm, and a wind speed of 3.0 meters per second, at the mid-span of each device was essentially 1,000,000.

DATA REDUCTION

As was expected, measurements made during the tests were unsteady. The combined effects of inflow variations, gravity, and blade dynamic responses, for example, resulted in a notable change in the root bending moments as a function of time. Because of these effects, all measurements were averaged over individual rotor rotations, or cycles, for a total of approximately thirty revolutions. To assure quality results, data with yaw errors greater than fifteen degrees was excluded during this averaging process.

The cycle-averaged blade-root moments were normalized by the corresponding dynamic pressure and curve-fit (using a forth-order polynomial) as a function of angle of attack, for each device configuration and deflection angle (δ). The resulting functions facilitated identifying differences in the root bending moments over a continuous range of angles of attack.

Since the blade-root strain-gages measured the entire blade's behavior, not just that of the device, it is not possible to calculate absolute device aerodynamic coefficient values (e.g., C_l and C_d). However, a measure of the device's effect can be identified by simply taking the difference between deflected and non-deflected root bending moments. It is assumed that the observed changes in root moments are a direct result of the

device configuration and deflection. These changes are described using normal-force (C_n) and suction-force (C_s) "delta-coefficients," that are defined as follows.

$$\Delta C_n = [M_{F\delta}/q_\delta - M_{Fo}/q_o] [1/(Sr)]$$

$$\Delta C_s = [M_{E\delta}/q_\delta - M_{Eo}/q_o] [1/(Sr)]$$

Where M_F and M_E are, respectively, the blade-root flap and edgewise moments at a corresponding flow dynamic pressure " q ." The subscript " δ " indicates a deflected (i.e., $\delta > 0$) control device configuration and the subscript " o " represents a "baseline" undeflected (i.e., $\delta = 0$) case. " S " is the blade area over which the device is active and " r " is the radial distance to the device centerline. " ΔC_n " represents the change in the aerodynamic normal force (i.e., in a direction perpendicular to the chord line) and is hence related directly to the blade flap moment. " ΔC_s " represents the change in the suction force (i.e., in a direction parallel to and forward along the chord line) and thus directly influences the blade edgewise moment.

The undeflected Spoiler-Flap configuration was used as the baseline case, from which all delta-coefficients were calculated, including for the Vented and Unvented Aileron configurations. The Spoiler-Flap was selected as the baseline because it most resembled an unmodified blade, in that it had the least aerodynamic shape deviation from a S809 airfoil.

The delta-force coefficients can be utilized to calculate the more familiar lift and drag coefficient values by applying the following equations.

$$\Delta C_l = \Delta C_n \cos \alpha + \Delta C_s \sin \alpha$$

$$\Delta C_d = \Delta C_n \sin \alpha - \Delta C_s \cos \alpha$$

The dynamic pressure and angle of attack are calculated at the device mid-span, as follows.

$$q \cong 1/2 \rho [V_{wind}^2 + (\Omega r)^2]$$

$$\alpha \cong \tan^{-1} [\Omega r / V_{wind}] + \beta$$

Where the air density (ρ) is calculated based on the average air temperature and pressure and " V_{wind} " is calculated as the time average of the site anemometer readings. Device angle of attack (α) is approximated by resolving the device mid-span rotational velocity vector (Ωr), the average wind speed (V_{wind}), and the blade pitch angle (β) into the appropriate directions. The above equations obviously ignore the induced velocity components, produced as a result of the blade's "action" on the flow.

RESULTS AND DISCUSSION

Figures 3 - 8 show the delta-lift and delta-drag coefficients observed for the various device configurations examined. Recall, for good turbine braking performance a large negative change in ΔC_l and a large positive increase in ΔC_d is desirable. Of prime interest in the plots are differences from the infinite-span wind tunnel data obtained by Ramsay, Janiszewska, and Gregorek.⁷

In most cases, the infinite-span data shows that stall occurs at an angle of attack of approximately 17 degrees. Most significantly, a notable change in the ΔC_l variation is noted around this condition. In contrast, the finite-span cases do not exhibit the same variation in behavior. This situation is to be expected and is likely the direct result of the three-dimensional flow that develops due to the finite-span geometry. The stall behavior for infinite-span wings (i.e., airfoils) is similarly "softened" or changed as the span-to-chord ratio (i.e., aspect ratio) is reduced.

In almost all cases, for the Spoiler-Flap and Vented Aileron, the lift loss observed for finite-span was less than that noted in the wind tunnel data. Except around stall, the 22.5% span device generates ΔC_l values most similar in magnitude to the infinite-span results. Interestingly, the shorter (i.e., 7.5%) span devices appear to generate a greater reduction in lift coefficient.

Figure 4 shows the Spoiler-Flap's variation of delta-drag coefficient (ΔC_d). As might be expected, the finite-span data predicts a slightly lower increase in the drag coefficient than is observed for an infinite-span configuration. The 15% and 22.5% span devices generate similar changes in the drag for angles of attack above approximately 17 degrees.

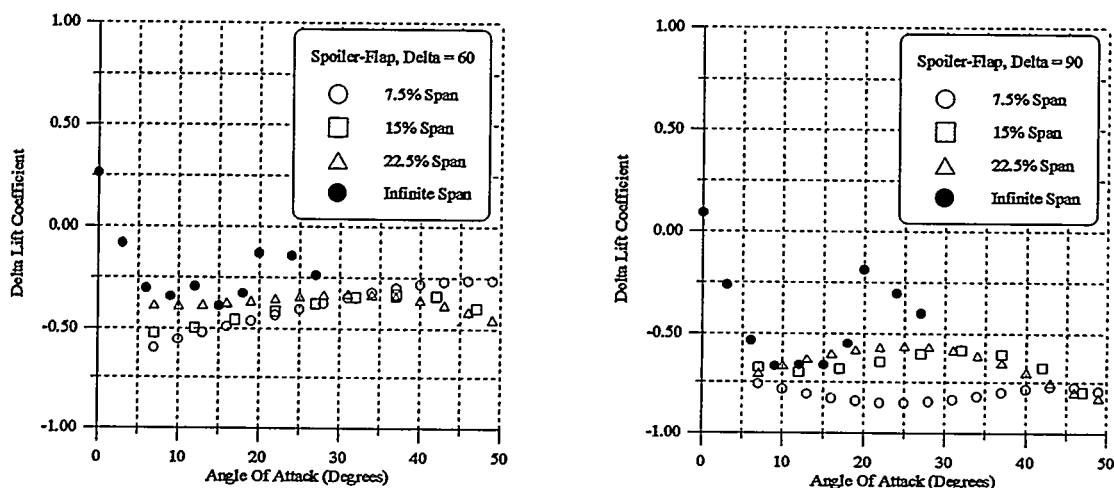


FIGURE 3 SPAN EFFECTS ON SPOILER-FLAP LIFT COEFFICIENTS.

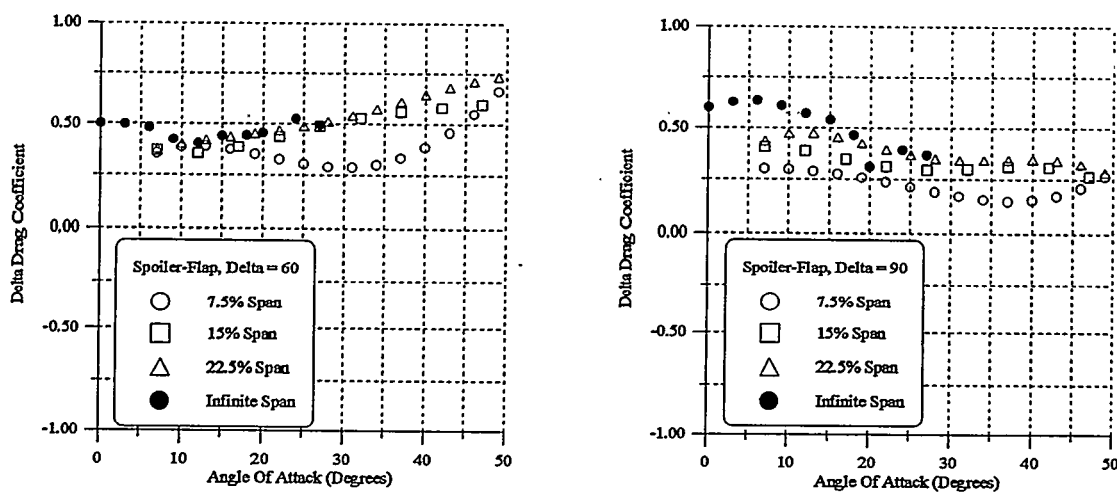


FIGURE 4 SPAN EFFECTS ON SPOILER-FLAP DRAG COEFFICIENTS.

Figure 5 shows the Vented Aileron's delta-drag coefficient (ΔC_d) behavior. Interestingly, at higher angles of attack (i.e., $\alpha > 20$ degrees) the shorter span device offers the better (i.e., higher) drag performance.

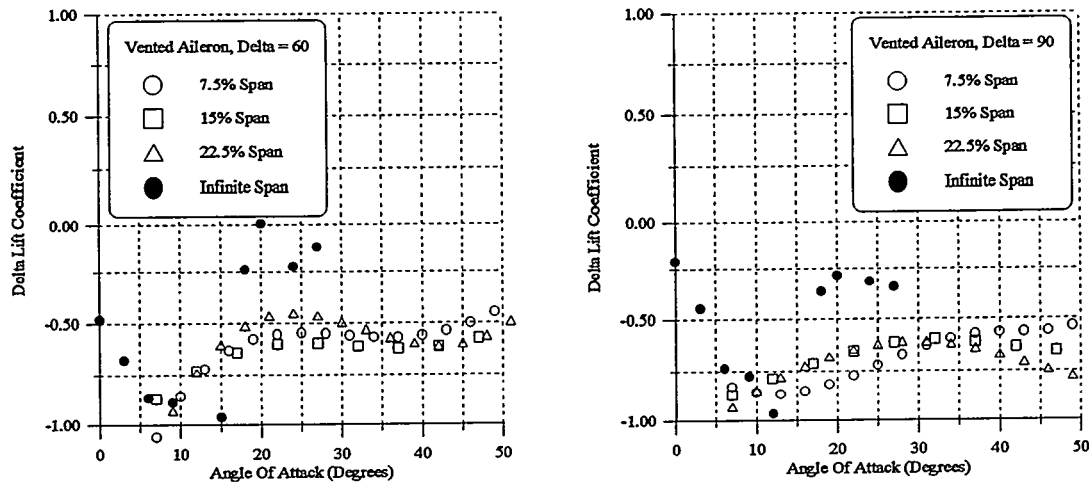


FIGURE 5 SPAN EFFECTS ON VENTED AILERON LIFT COEFFICIENTS.

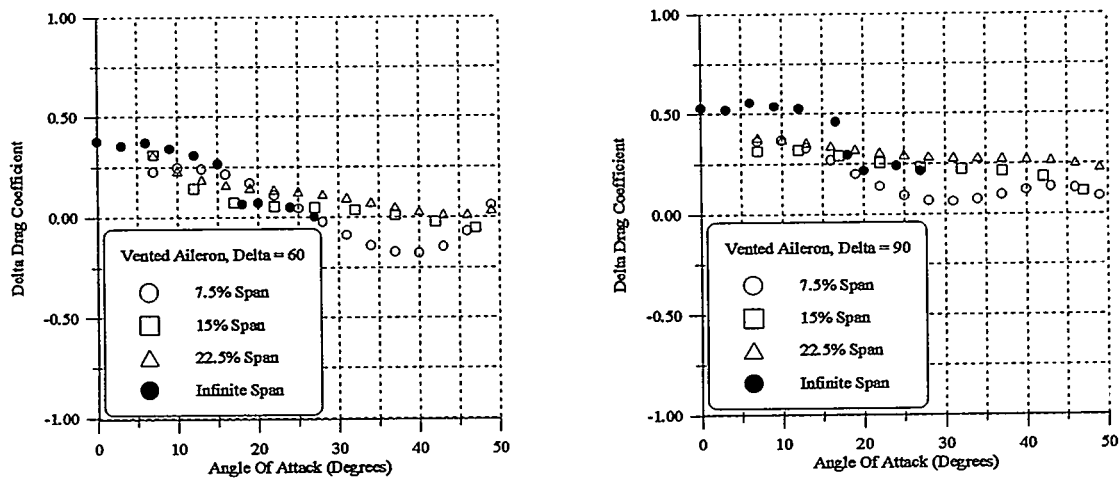


FIGURE 6 SPAN EFFECTS ON VENTED AILERON DRAG COEFFICIENTS.

Figure 7 shows the Unvented Aileron delta-lift coefficient (ΔC_L) behavior. Please note that the ordinate in these plots has been shifted since the negative camber of the Unvented Aileron configuration produces extremely large reductions in lift. For angles of attack less than 15 degrees, the infinite and finite-span data are very similar. Interestingly, for angles of attack above 15 degrees, the shorter span device generated the larger reduction in lift coefficient.

Figure 8 identifies the Unvented Aileron delta-drag coefficient (ΔC_D) behavior. As was the case for lift, the drag coefficient effects are very similar, regardless of span, at angles of attack below approximately 15 degrees. At higher angles of attack, the larger (i.e., >15%) span devices offer a greater increase in drag coefficient.

Unfortunately, data for a 60 degree device deflection (δ) and 22.5% span Unvented Aileron is missing in Figures 7 and 8. It was discovered, after the tests were completed, that the data for this condition were corrupted.

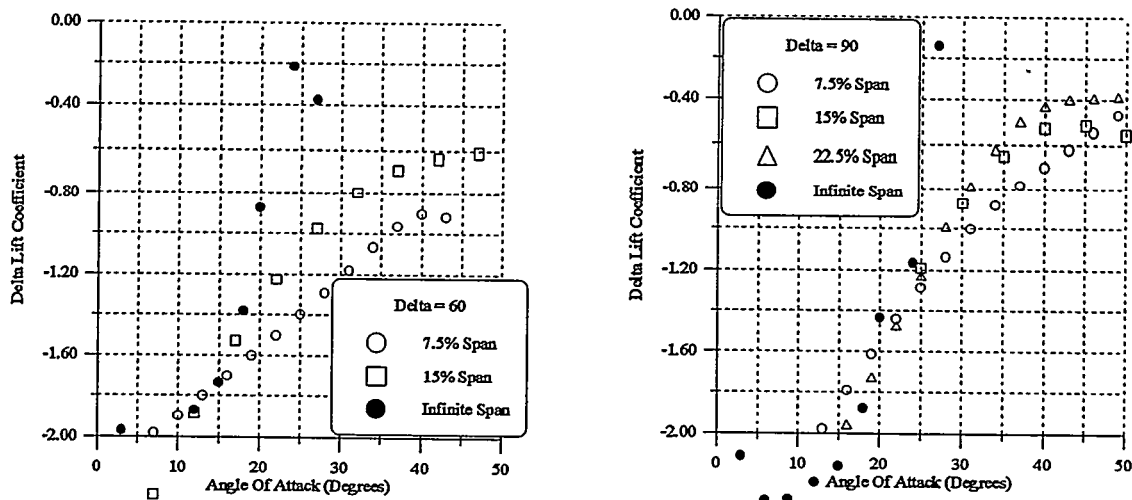


FIGURE 7 SPAN EFFECTS ON UNVENTED AILERON LIFT COEFFICIENTS.

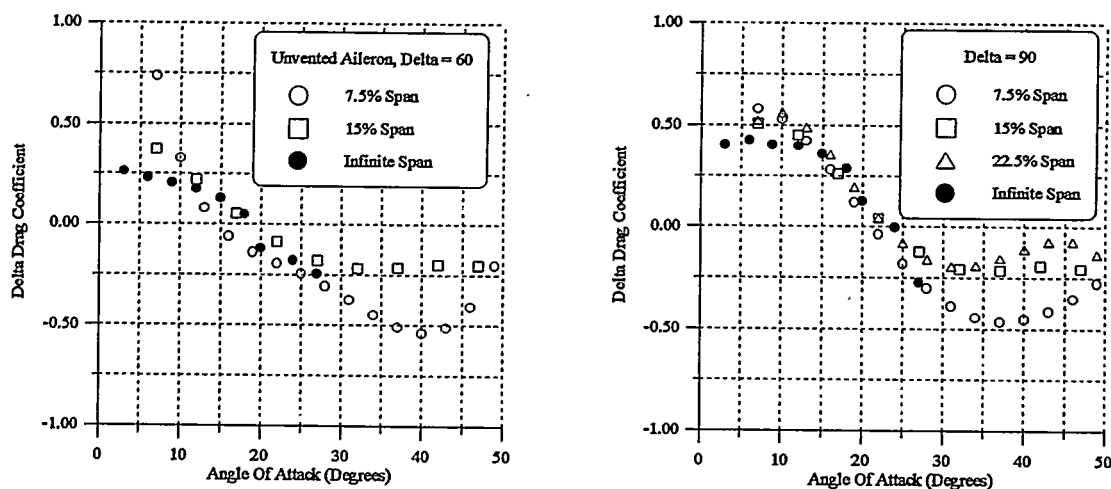


FIGURE 8 SPAN EFFECTS ON UNVENTED AILERON DRAG COEFFICIENTS.

OBSERVATIONS AND DISCUSSIONS

It is important to identify, if possible, a means for estimating the change in device performance from infinite-span to finite-span cases. Consequently, some observations of span effects, on the lift and drag behavior, are offered. The ideas and comments apply in a general sense to each of the three configurations examined (i.e., the Spoiler-Flap, Vented Aileron, and Unvented Aileron).

Changes in the ΔC_l curves, around stall or approximately 17 degrees angle of attack, are less abrupt when compared to the variations observed for the infinite-span devices. Such effects are typical as a result of aspect ratio reductions, and are observed for other similar geometry's like wings and flat plates.

More interesting is the observation that the shortest span device appears to produce the largest reduction in lift coefficients. This effect seems unreasonable and suggests that some other phenomena may be contributing to the observed results. Perhaps the unmodified inboard part of the blade is being affected notably as a result of the device deflection. By unloading the device portion of the blade, a strong shed vortex could be forming at an effectively new blade tip, so as to induce a notable reduction in the angle of

attack on the inboard working part of the blade. This angle of attack reduction would in turn cause a drop in the blade flapping load and hence could be incorrectly interpreted as a device (alone) effect, when in reality it is also an inboard blade effect. The vortex strength and its influence would diminish as the effective blade tip moved inboard, thus explaining why the ΔC_1 magnitude drops as the device span is increased. A great deal of time and effort was expended to verify this hypotheses and to analytically quantify the effect. Unfortunately, a simple correction scheme was not identified.

As was noted in much of the data presented earlier, the shortest (i.e., 7.5%) span configuration typically produced the smallest drag change (i.e., ΔC_d) and, as might be expected, the infinite-span device produced the greatest change in drag. Most significantly, the 15% and 22.5% span devices behaved similarly and the drag increments were only slightly smaller in magnitude than for the infinite-span case. This particular drag behavior is consistent with that observed for other bodies or shapes¹¹.

As is shown, by Hoerner, for simple geometries with height-to-span ratios below approximately 0.20 the drag coefficient changes rapidly¹¹. At height-to-span ratios above 0.20 the drag behavior is nearly constant and roughly 60% of the infinite-span value. Figure 9a illustrates this effect, for a rectangular plate and a circular cylinder. Hoerner further suggests an approximate expression for the observed effects (equation 29, p 3-15). Specifically,

$$\lambda \equiv [(C_d)_{3D}/(C_d)_{2D}] \cong 1 - K(h/b)$$

Where λ is the ratio between the finite and infinite-span drag coefficients, h is the plate height, b is the plate span, and K is a constant of order 5.0. It is proposed that the above equation can be modified to fit the current applications, as follows.

$$\lambda_d \equiv [(\Delta C_d)_{3D}/(\Delta C_d)_{2D}] \cong 1 - K'(c_c/\Delta r)$$

Where λ_d is now the ratio between the finite and infinite-span delta-drag coefficients, c_c is the device chord, Δr is the device span, and K' is again a constant. Based on a limited amount of data, for the configurations examined in this investigation, a value of K' equal to approximately 1.1 appears to best fit the results.

Figure 9b compares the results predicted for a 7.5% span Spoiler-Flap ($c_c/\Delta r = 0.485$ and $\lambda_d = 0.47$), as obtained by applying the above expression to the infinite-span data. The most notable differences are observed around stall. λ_d values for the 15% and 22.5% span devices are, respectively, 0.73 and 0.82 and very close to values noted from the atmospheric tests.

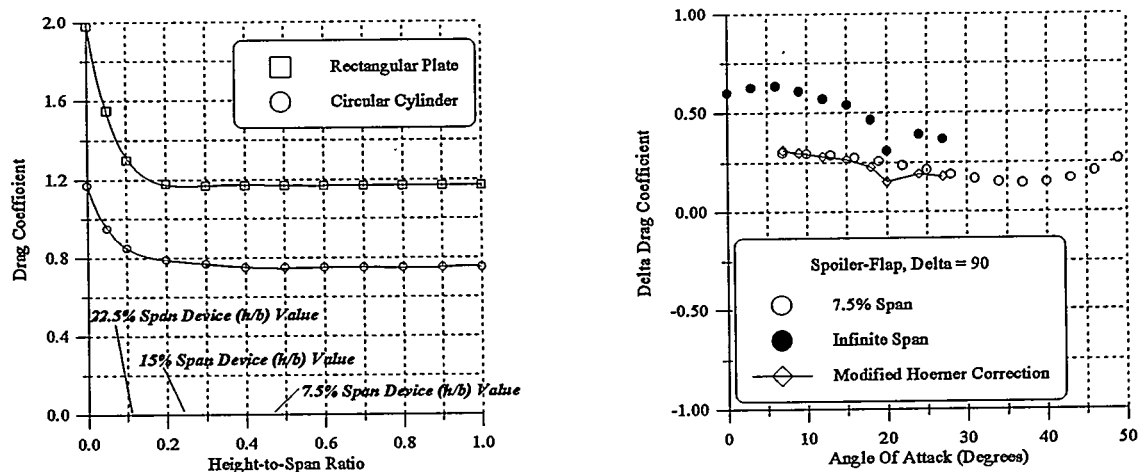


FIGURE 9A & 9B SIMPLE HEIGHT-TO-SPAN RATIO DRAG EFFECTS¹¹ AND AN EXAMPLE OF DRAG CORRECTION FOR 7.5% SPAN SPOILER-FLAP.

Regardless of the proposed equation's accuracy, the basic trends noted by Hoerner appear to apply to current investigation's drag results. Formulation of an exact equation is a difficult proposition, since the shapes of interest (i.e., aerodynamic controls) are more complicated than rectangular plates or circular cylinders. In addition, the control surface is typically positioned behind an upstream element and there are notable wake interaction effects.

CONCLUSIONS

On the basis of the investigation results the following conclusions are offered.

- 1) The most pronounced lift behavior differences, between the atmospheric and wind tunnel test data, were for angles of attack around stall. Changes in the finite-span lift coefficient data were more constant in comparison to the infinite-span data. This effect on the stall behavior is likely a direct consequence of having a device of lower aspect ratio.
- 2) For device spans greater than 15% the differences in lift coefficient behavior, relative to the infinite-span data, are typically small (with exception to the stall region as was noted above). Results for the shortest span (i.e., 7.5%) devices appear to be influenced by inboard blade and shed vortex induced velocity effects.
- 3) Drag differences, as a function of span, appear to follow aspect ratio trends noted for similar geometry's (i.e., flat plates and cylinders). Specifically, the smallest drag changes occur for devices of the shortest span. The drag increments for devices of spans greater than 15% appear similar in magnitude and are approximately 70% of the infinite-span values. A simple model predicting the drag increment of a finite-span device, as a function of aspect ratio, is offered.
- 4) The Unvented-Aileron lift and drag behavior appears less affected as a result of finite-span. This result suggests that the openings or vents, associated with the Spoiler-Flap and Vented Aileron geometry, have an impact on the three-dimensional character of the flow field.

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USING PARTIAL SAFETY FACTORS IN WIND TURBINE DESIGN AND TESTING

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ABSTRACT

This paper describes the relationship between wind turbine design and testing in terms of the certification process. An overview of the current status of international certification is given along with a description of limit-state design basics. Wind turbine rotor blades are used to illustrate the principles discussed. These concepts are related to both International Electrotechnical Commission and Germanischer Lloyd design standards, and are covered using schematic representations of statistical load and material strength distributions. Wherever possible, interpretations of the partial safety factors are given with descriptions of their intended meaning. Under some circumstances, the authors' interpretations may be subjective. Next, the test-load factors are described in concept and then related to the design factors. Using technical arguments, it is shown that some of the design factors for both load and materials must be used in the test loading, but some should not be used. In addition, some test factors not used in the design may be necessary for an accurate test of the design. The results show that if the design assumptions do not clearly state the effects and uncertainties that are covered by the design's partial safety factors, outside parties such as test labs or certification agencies could impose their own meaning on these factors.

INTRODUCTION

The use of partial safety factors in wind turbine design is common practice and is, in principle, accepted by International Electrotechnical Commission (IEC) and other international organizations as a practical means for achieving sound designs [1]. The technique stems from an ISO standard on limit-state design theory, which describes actions (loads) and resistances (strengths) associated with a structure [2]. In the design process, partial safety factors are applied to either the loads or the strengths to account for their respective uncertainties. Throughout the world, numerous design codes exist that specify the various partial safety factors to be applied, however little agreement exists among the available codes [3]. This creates a problem if certain codes are to be recognized outside their traditional boundaries. The problem is complicated more when insufficient background or guidance is given to describe how a partial safety factor is to be applied and what influence or uncertainty it accounts for. Sometimes a factor's intended purpose may be intentionally vague, or at least poorly understood. This may give designers some needed flexibility and may keep the codes from becoming too restrictive, but these ambiguities do not help the designer account for the true uncertainties represented by each partial safety factor or assure consistency between design approaches.

During a test, the best possible loading would produce a true representation of the intended design conditions. To develop the equivalent full-scale test loading for design verification, a combination of design safety factors and test-load factors are required. A test-load factor is applied on top of the design loads to account for design conditions not properly represented by the test. For example, test environments are less severe than operating conditions and this difference can be accounted for using a test-load factor. Also, uncertainty that is introduced when modifying the design loads to establish simplified and elevated test loads for the purpose of accelerating the test can warrant an additional test-load factor. These factors should be applied appropriately if the design is to be honestly evaluated. But this may not be possible unless each influence covered by the partial safety factor in both the design and

test is known and accounted for explicitly. Otherwise, these influences could easily be overlooked, or double-booked, when establishing the test conditions.

Wind turbine blades are among the most critical components in the turbine design and provide a good basis for illustrating the application of partial safety factors for different design codes. For this paper, the discussion will focus on the rotor blade design and testing.

CERTIFICATION BACKGROUND

International certification has become a requirement for U.S. manufacturers to compete in many foreign markets. At present there are three international certification bodies active in the European wind turbine industry: Germanischer Lloyd (GL), Det Norske Veritas and Risø, and CIWI. Each certification body has developed its own interpretation, and therefore rules and requirements for Type Certification, the process by which a specific turbine type is certified by independent review of design, testing, and manufacturing documents and records. One of the more consequential differences among the different organizations' rules is the treatment of partial safety factors.

Recognizing the problem, the European Community (EC) encouraged harmonization of the different certification rules in order to facilitate trade within Europe. Over the past 5 years, this has resulted in active standards development programs on the international level. The IEC has supported the development of several standards that are intended to be the basis for a set of harmonized standards. European certification bodies plan to take a step toward harmonization by adopting the IEC standard in addition to their own national requirements in the future. Within the EC, certification procedures will still likely depend on national requirements, but the IEC international standards will be the basis for international certification procedures.

Certification of wind turbines in the U. S. is not required. As a result, most U.S. turbine manufactures did not pursue certification until recently. Because the international market is now stronger than the domestic market, interest in certification by U.S. manufacturers has increased; however, there currently is no U.S. certification body, nor is there an established set of U.S. standards on which to base a certification process. The National Renewable Energy Laboratory (NREL) and the American Wind Energy Association have been active in the IEC standards development effort in anticipation of using these standards in a U.S. certification program. NREL has developed certification testing capability and design review requirements that conform to IEC Type Certification requirements.

LIMIT-STATE DESIGN

The IEC 1400-1 wind turbine design standard is based on ISO 2394 "General Principles on Reliability for Structures." This standard specifies limit-state design procedures that use partial safety factors to manage uncertainty in various steps in the design process. The partial safety factors are dependent on the uncertainties in loads and materials, the uncertainties in the analysis methods, and the importance of structural components with respect to the consequences of their failure.

To assure safe design values for loads and material properties, the uncertainties and variability in load predictions (characteristic load values) and material properties (characteristic strength properties) are adjusted by partial load and material design factors. In IEC 1400-1 the alternative term "representative value" is used in some cases, where a characteristic value is not easily evaluated statistically.

Equation 1 defines design loads and Equation 2 defines design material properties according to ISO 2394 and IEC 1400-1.

$$F_d = \gamma_f F_k \quad (1)$$

where:

F_d are the design values for loads
 γ_f are the partial load factors
 F_k are the characteristic values for loads.

$$f_d = \frac{1}{\gamma_m} f_k \quad (2)$$

where:

f_d are the design values for material properties
 γ_m are the partial material factors
 f_k are the characteristic values (e.g., strength) of material properties.

A consequences of failure partial safety factor, γ_n , is adopted in IEC 1400-1 to distinguish between:

Component class 1: Used for "fail-safe" structural components whose failure does not result in the failure of a major part of a wind turbine generator system (WTGS);

Component class 2: Used for "non fail-safe" structural components whose failures lead rapidly to the failure of a major part of a WTGS.

Typically, γ_n is applied to class 2 components, such as wind turbine blades, which are not fail-safe by design.

The general equation for non-exceedance of the ultimate limit-state [2] is:

$$\gamma_n \cdot S(F_d) \leq R(f_d) \quad (3)$$

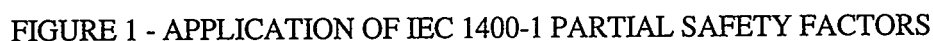
Each type of analysis requires a different formulation of the load and strength functions, S and R respectively, and deals with different sources of uncertainties through the use of safety factors. In general, static-strength design cases are usually evaluated with a different set of factors than the fatigue design cases, because the failure modes are different and the uncertainties are dependent on the type of loading used. Equation 3 is important to the following discussion, especially in developing the test loading, because it shows that the partial safety factor for consequences of failure is applied to the load (left) side of the equation.

Most design codes address partial safety factors for both load and strength individually and in accordance with Equations 1 and 2. According to IEC 1400-1, the partial load safety factors are meant to account for the possibility of unfavorable deviations of the load from the characteristic value, and uncertainties in the loading model. The partial material safety factors are meant to account for the possibility of unfavorable deviations of material strength from the characteristic value, inaccurate prediction of the load-carrying capacity of the structure, uncertainties in geometry, and uncertainties in converting the material properties measured on the test control specimens (coupons) to the material properties of the structure.

Of primary importance with the design-application of material partial safety factors is the adjustment of composite material properties from small coupon data to the full-scale structure. Material property adjustments may be necessary to correct for the effects of moisture, temperature, ultraviolet radiation,

Some codes account for these different influences individually, using separate safety factors for each concern, but generally offer weak rationale. Others lump the load-related uncertainties into one factor, γ_f , and the material related factors into another factor, γ_m . For blade design verification tests, some of the design partial safety factors are applied to the test load and some are not. To represent the test load accurately, the material partial safety factor in the design must be subdivided into smaller components so that the uncertainties that are accurately accounted for in the test can be separated from those that are not. Most design codes do not recognize this constraint. This paper gives clarification on how partial material factors and consequences of failure factors should be applied for blade testing to avoid inconsistent accounting of the various factors by testing organizations, certification organizations, and designers.

Figure 1 gives a schematic representation of the IEC 1400-1 design safety standards for both static and fatigue cases as they existed in the April 1997 draft revision. The sample cases shown are for wind turbines having ultimate limit loads driven by extreme aerodynamic forces. The standard assumes that the material strength data is normally distributed with a 10% coefficient of variation (COV), but it gives guidance for other COVs when data is available.



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however, the coupon strengths must already be corrected to account for a number of more deterministic influences including, scale effects, creep, degradation due to external actions (e.g., humidity, temperature, ultraviolet radiation), and defects that would not normally be detected (e.g., fiber alignment, fiber volume). In addition, the characteristic coupon strengths are also adjusted beforehand to a 95% survival probability with 95% confidence for the assumed COV of 10%.

IEC 1400-1 does not give procedures or partial safety factors for making coupon strength corrections to account for the numerous deterministic adjustments listed above. Designers are left to develop their own adjustments based on independent testing, published test data, or analysis, and provide the sufficient justifications [e.g., 4, 5, 6, 7]. This process can be complex and laborious, but may be advantageous for design optimization, because material property adjustments are very dependent on the specific materials used and the details of the design. Therefore the adjustments are best if determined on a case-by-case basis. This adjustment is illustrated in the figure as the difference between the coupon strength database distribution and the adjusted coupon strength distribution. The final partial safety factor of 1.1 is applied only to account for the uncertainty in shifting from the corrected coupon strengths to the actual blade.

The partial load factors for ultimate limit-state load cases range from 1.1 to 1.45, depending on the source of loading, and is given in tabular form in IEC 1400-1. Most commonly, the source of the extreme loads would be aerodynamic, such as with an extreme gust event, operational, such as a high wind shutdown. The factors used for these events would be 1.35 and 1.45, respectively. No adjustment is required under IEC rules to cover the consequences of failure for ultimate limit-state cases.

For fatigue, no partial safety factor is required to directly cover load uncertainty. However, a partial safety factor of 1.15 is required to cover the consequences of failure, γ_n , for rotor blades because they are non-fail-safe components. Based on ISO 2394, the partial safety factor, γ_n , can be considered a load factor because it is applied to the load function, $S(F_d)$, in Equation 3.

For IEC 1400-1, the product of all the partial safety factors combined is greater in the ultimate case ($\gamma_n \cdot \gamma_m \cdot \gamma_f = 1.485$) than in the fatigue case ($\gamma_n \cdot \gamma_m \cdot \gamma_f = 1.265$). However, it is impossible to assign a number that represents the total design adjustments made for either IEC case, because most of the material adjustments, which are design dependent, are not explicitly specified. The 1.1 material factor is only given as a minimum starting point.

GERMANISCHER LLOYD - PARTIAL SAFETY FACTORS

The German certifying agency, Germanischer Lloyd (GL), has a design code that is often used by wind turbine manufacturers for certification [8]. Figure 2 gives a schematic representation of our interpretations of the GL Standard from Chapter 5 on rotor blades, for both ultimate strength and fatigue cases using glass reinforced plastics (GRP). Other materials are addressed, but the bulk of the code deals with GRP blades.

In contrast to the IEC, the GL standard prescribes all of the individual factors to be applied for each influence of concern on the material side. None of the adjustments are left to the designer, however, the meaning of each factor is not always fully given.

Both the ultimate strength and the fatigue cases use the static coupon strengths as a basis. For the ultimate limit-state, or strength verification, a series of five partial safety factors are given: C_{1a} , C_{2a} , C_{3a} , C_{4a} , and C_{5a} . As shown in Figure 2, the product of these factors, γ_m , is applied to the material strengths, as in Equation 2. The first factor, C_{1a} , is a general safety factor of 1.35 and may, in the authors' opinion,

cover such influences as consequences of failure, modeling uncertainty, scale effects, and manufacturing defects. The exact purpose of this factor is not specified.

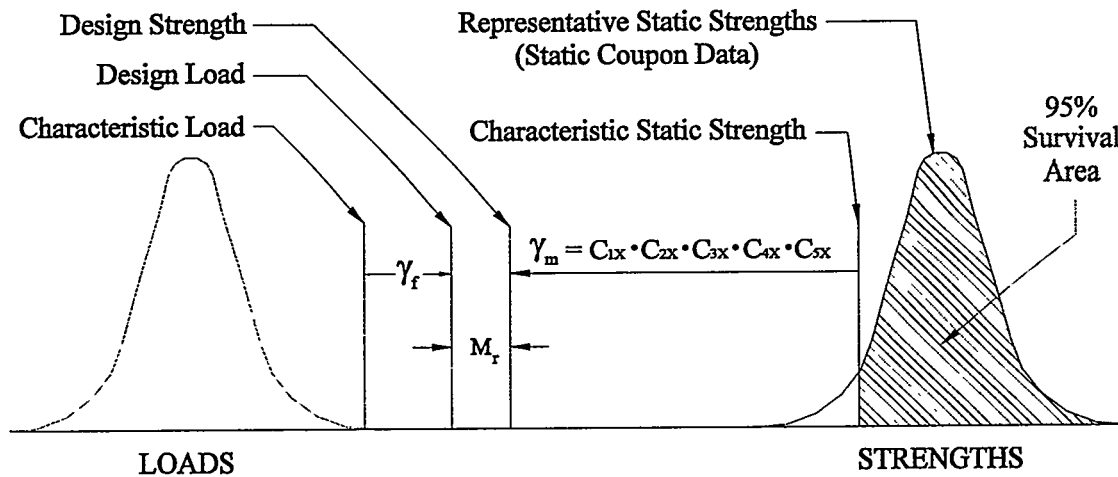


FIGURE 2 - GERMANISCHER LLOYD PARTIAL SAFETY FACTORS FOR ROTOR BLADES

A value of 1.5 is assigned to C_{2a} to account for creep strength, but a more elaborate description is not given. A value of 1.1 is applied to C_{3a} to account for temperature effects in the operating environment. C_{4a} accounts for the laminate quality where prepreps are given preference over hand layups. The values assigned to these factors are 1.1 and 1.2, respectively. Finally, C_{5a} is a factor used to account for uncertainties in the resin cure method used. Tempered laminates are not penalized, while untempered laminates require a factor of 1.1 to be applied. The product of these material factors results in a total factor for ultimate strength of between 2.45 and 2.94, applied to the characteristic values of coupon strength with a 95% probability of survival.

For fatigue, a similar series of partial safety factors is given as C_{1b} , C_{2b} , C_{3b} , C_{4b} , and C_{5b} . The first factor, C_{1b} , is the general safety factor of 1.35. In addition to the influences listed for the strength verification case, this factor may cover uncertainty of material properties for the given lifetime, or uncertainty in the fatigue formulations used (e.g., Goodman relations, Miner's summation). The factor C_{2b} gives specific guidance for shifting the static coupon strengths to fatigue strengths for either epoxy or polyester matrices. As with the ultimate case, C_{3b} deals with temperature effects in the operating environment and is assigned a value of 1.1. C_{4b} addresses fiber alignment and fatigue sensitivity by penalizing blades made from woven or non-continuous fibers with a factor of 1.2. Blades made from continuous, non-woven fibers have a factor of 1.0. C_{5b} is identical to the factor, C_{5a} , in the ultimate strength case. The product of these material factors results in a total fatigue factor of between 1.485 and 1.96 that is applied to the uncorrected coupon fatigue strengths (excluding C_{2b}).

The partial safety factor on loads required by Germanischer Lloyd to verify the ultimate strength case is 1.35 for the aerodynamic case in this discussion. For the GL fatigue case, a factor of 1.0 is used. This is the same as for the IEC fatigue case. However, the GL standard does not explicitly give a factor to cover consequences of failure for fatigue or ultimate strength.

IEC/GL COMPARISON

One way to judge the severity or conservatism of any code is to look at the product of the material and the load factors. This product will determine the margin between the loads and the strengths. Because GL prescribes the values to be used in correcting for each material effect, and IEC allows most of the corrections to be made by the designer, a direct comparison of total partial safety factors is difficult. But for the purposes of this discussion, it is worthwhile to make an attempt at this comparison in rough measures.

Tables 1 and 2 summarize the explicitly stated design partial factors for both the IEC and GL codes, for ultimate strength and fatigue.

TABLE 1 – PARTIAL SAFETY FACTORS FOR ULTIMATE STRENGTH ANALYSIS

<i>Partial Safety Factors</i>	<i>IEC 1400-1</i>	<i>Germanischer Lloyd</i>
Loads	1.35	1.35
Consequences of Failure	1.0	1.0
Materials	1.1*	2.45 – 2.94
Total	1.485*	3.30 – 3.96

* Excluding coupon material property adjustments

TABLE 2 – PARTIAL SAFETY FACTORS FOR FATIGUE ANALYSIS

<i>Partial Safety Factors</i>	<i>IEC 1400-1</i>	<i>Germanischer Lloyd</i>
Loads	1.0	1.0
Consequences of Failure	1.15	1.0
Materials	1.1*	1.485 – 1.96**
Total	1.265*	1.485 – 1.96**

* Excluding coupon material property adjustments

** Excluding C_{2b}

For ultimate strength, the IEC product of partial safety factors is 1.485. This excludes the material property adjustments, illustrated earlier in Figure 1, which were applied before, γ_m , the minimum material partial safety factor of 1.1. In the GL code, the total product of partial safety factors is between 3.30 and 3.96. Therefore, in order for the two codes to be equal with respect to ultimate strength, IEC designer-specified adjustments of between 2.22 and 2.67 would be necessary on the coupon material properties.

For fatigue, the IEC product of load and material partial safety factors is 1.265, including the factor for consequences of failure. As with the ultimate strength case, this excludes the designer-specified material property adjustments made before, γ_m , the material partial safety factor was applied. In the GL code, the product of partial safety factors is between 1.485 and 1.96, the same as the total material side factor. Making the same argument as the ultimate strength case, the IEC designer-specified material property corrections for fatigue would be between 1.17 and 1.55 to make the two codes equally severe.

As a general observation, it appears that the GL code is more severe with respect to ultimate strength criteria than for fatigue. The IEC ultimate strength and fatigue cases appear to be closer. Because the IEC designer-specified material adjustments add such a large variable it is difficult to determine which code is more severe in each case. From the authors' experience, however, it appears that GL may more stringent in the ultimate strength case where in fatigue IEC may be more stringent. These differences

illustrated above can result in design strength differences, but also can cause critical ambiguities in determining the blade test loads used for design verification.

TEST-LOAD FACTORS

Full-scale blade testing has become a common method of verification for wind turbine rotor blades, although there are few codes that require blade testing to be performed at this time. A typical design verification test used for certification checks the blade's ability to withstand an envelope of design load conditions. The test is considered successful if the blade survives the prescribed test loading without a failure. Further information about failure modes, manufacturing quality, and reserve strength can be obtained if the testing is continued to blade failure.

During a test, the best possible loading would produce a true representation of the intended design conditions. To develop the equivalent full-scale test loading for design verification, a combination of design safety factors and test-load factors are required. First the design-load partial safety factors are applied to the characteristic loads, because the same load uncertainties in the design analysis are inherent to the test procedures.

A significant portion of the material-design partial safety factor is ignored for the test loading, because the material in the blade being tested embodies most of the specific material properties that the factors are intended to cover. However, the component of the material-design partial safety factor that accounts for degradation due to environmental effects such as humidity, temperature, and ultraviolet radiation is usually not properly represented in the laboratory conditions. For the purpose of establishing a representative test load, this component of the material partial safety must be applied as a test-load factor.

Additional test-load factors may also be necessary to account for uncertainties introduced by the test equipment and test-load formulations. These uncertainties might arise due to errors in using or applying the S-N or Goodman relations when modifying the test loads to accelerate the test time or to simplify the test loading to fit laboratory equipment limitations [9].

The above approach for establishing the test loads is technically consistent with limit-state design theory, but differences among the various codes in the treatment of design partial safety factors are passed on to the test, and in some cases, amplified. As mentioned earlier, the product of the material and load factors indicates the severity of a given code. But when a large portion of the material factor is ignored for the test, the relative importance of the load factors is increased. Following this approach, two blades with essentially the same design requirements and strength could have significantly different test requirements.

This incongruity is illustrated in Table 3 using the two codes mentioned above. Applying the above method for establishing a fatigue test load, the IEC test loads would probably be higher than the GL test loads. This is because γ_n equal to 1.15, covering consequences of failure, is applied to the IEC test loads, while GL has no load factors. Because environmental effects are treated differently between the two codes, this would cause further differences between the respective test loading.

TABLE 3 – LOAD FACTORS FOR FATIGUE TESTING

<i>Test-load Factors</i>	<i>IEC 1400-1</i>	<i>Germanischer Lloyd</i>
Design Load Factor	1.0	1.0
Consequences of Failure	1.15	1.0
Materials Factor	Environmental Effects	Environmental Effects
Total Test-load Factor	1.15 x Environmental Effects	Environmental Effects Only

STRENGTH-BASED TESTING

Another approach that is used to develop loading for blade tests is a strength-based method. While this method is more likely to be requested by a blade designer, it can also be used as a design-verification test for certification. More often strength-based test loads are used as a verification of as-built strength. Loading is based on the design material strength properties for the blade structure rather than a design-load envelope, and they are usually less complicated to develop. Strength-based testing tends to load the blade more uniformly in terms of the spanwise strain distribution, and often results in a blade failure. The basic manufacturing and material assumptions are checked when this method is implemented. Figure 3 shows the relationship between the design and test-load factors for both strength and load-based tests.

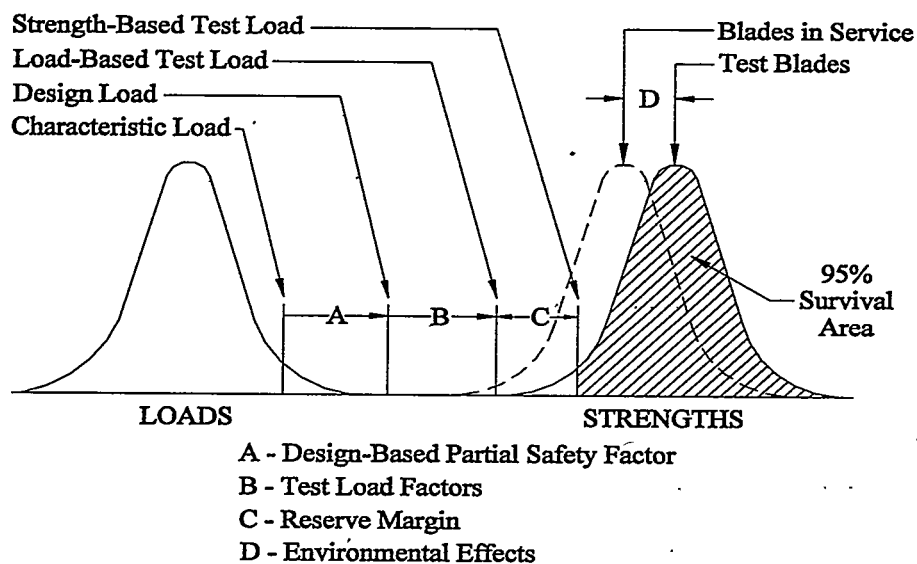


FIGURE 3 - GENERALIZED APPLICATION OF LOAD FACTORS FOR WIND TURBINE TESTING

Note that the strength-based loading is more severe because it includes the blade's reserve strength. Also shown is the relationship between the test blades and the blades in service. The more severe operating environment of the in-service blades lowers their strength.

CONCLUSIONS

This paper describes the growing importance of wind turbine certification in terms of the rotor blades. The latest revision of IEC 1400-1, "Wind Turbine Generator Systems, Part 1: Safety Requirements," is compared to the Germanischer Lloyd counterpart "Non-Marine Technology, Part 1 Wind Energy, Regulation for the Certification of Wind Energy Conversion Systems" by explicitly comparing the rule governing wind turbine blade design. Areas of ambiguity were described. In general, it appears that IEC 1400-1 might have a less conservative treatment of ultimate strength design criteria while the treatment of the fatigue analysis might be more conservative under IEC. This comparison is difficult to confirm, however, because most of the material adjustments made under IEC rules are not explicitly given.

A general procedure given for determining test loading for load-based design verification tests shows that design code differences, particularly in the treatment of partial safety factors, can lead to significant differences in how two blades are tested.

ACKNOWLEDGEMENTS

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SOURCES OF FATIGUE DAMAGE TO PASSIVE YAW WIND TURBINE BLADES

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ABSTRACT

Using an integrated computer analysis approach developed at the University of Utah, fatigue damage sources to passive yaw wind turbine blades have been investigated. Models of a rigid hub and teetering hub machine reveal the parameters important to the fatigue design of each type. The teetering hub proved much less susceptible to fatigue damage from normal operation loads. As a result, extreme events were critical to the teetering hub fatigue life. The rigid hub blades experienced extremely large gyroscopic load cycles induced by rapid yaw rates during normal operation. These yaw rates stem from turbulence activity which is shown to be dependent upon atmospheric stability. Investigation revealed that increasing yaw damping is an effective way of significantly reducing these gyroscopic fatigue loads.

INTRODUCTION

An integrated approach to wind turbine fatigue analysis has been developed at the University of Utah (Laino and Hansen, 1997). A suite of programs including SNLWIND-3D (Kelley, 1993) to generate simulated turbulence, YawDyn (Hansen, 1992) and ADAMS (Davis, 1996) to conduct dynamic analysis, and LIFE2 (Schluter and Sutherland, 1989) to estimate fatigue damage are used together to determine the relative importance of different parameters to wind turbine fatigue life.

Preliminary results from analysis of the rigid hub Combined Experiment Rotor (CER) revealed a strong correlation of fatigue damage with free yaw operation. This paper investigates the sources of these damaging fatigue loads, and how they might be alleviated. A passive yaw, teetering hub machine is investigated as well to determine the fatigue design drivers for this fundamentally different wind turbine design concept.

TURBINE MODELS

YawDyn models of two wind turbines - a rigid and a teetering hub - were used to calculate flap moment loads for the fatigue analyses. Fatigue models were also developed for both turbines. For the rigid hub, two fatigue models were developed, one based on previous work and the other created to permit direct comparison to the teetering hub results. Details of these models are discussed below.

Teetering Hub

A teetering hub turbine with a 26 m diameter rotor rotating at 58 rpm was modeled at 25 m hub-height with ± 2.5 degrees of free teeter out of the nominal rotor plane. The rotor is downwind of the tower in a free yaw state, and has 7 degrees of pre-coning. YawDyn simulations were conducted using simulated full-field turbulence generated using SNLWIND-3D with the IEC (International Electrotechnical Committee) specified Kaimal spectrum.

For the fatigue model, assumptions are made similar to those made by Sutherland and Kelley (1995). Namely, the blade design is such that the nominal strain level never exceeds 0.4%. It is further assumed this strain level occurs at twice the sum of the average load plus 4 standard deviations occurring at 15 m/s (on a ten minute average) hub-height wind speed. It is important to keep in mind that this assumption specifies normal operation loads as the fatigue design criteria, which has a bearing on how the results are interpreted.

The material properties used to evaluate the teetering rotor blades are for GP 0/45 laminates (glass reinforced polyester with fibers in the load direction (0) and plus and minus 45 degrees (45) to this direction) based on the data compiled by DeSmet and Bach (1994). For this fatigue model, a load to stress conversion of 0.57 MPa/kN·m is used to process the flap moment data.

Rigid Hub

The Combined Experiment Rotor is a well documented, rigid hub performance test bed operated at the National Wind Technology Center. Details about this down wind, passive yaw turbine and its instrumentation can be found in Fingersh, et al. (1995). A YawDyn model of the CER was used for this project and simulation results were compared to test data for model verification. For input to YawDyn, wind files were generated from anemometry data for comparison to test data; and SNLWIND-3D was used to investigate turbulence parameters.

Two fatigue models of the CER blade root are used in this project. The first is as described by Laino and Hansen (1997). This model is a hollow cylinder 20 mm thick and 80 mm outside diameter. The material is cast 8630 steel. The S-N curve used for this study is shown in Figure 1. This curve is a power law function based on cast 8630 fatigue data. The purpose of the power law function is to eliminate the fatigue limit evident in the data, which is a suggested method discussed by Veers (1988) to facilitate the use of Miner's linear damage accumulation rule with data demonstrating a fatigue limit. This fatigue model of the CER yields a load to stress conversion factor of 29.1 MPa/kN·m. This value was used to convert blade flap moments to stresses for most fatigue life analyses.

The other fatigue model of the CER blade was used to compare results of the two turbine models. In this case, the same assumptions made about fatigue design load and material

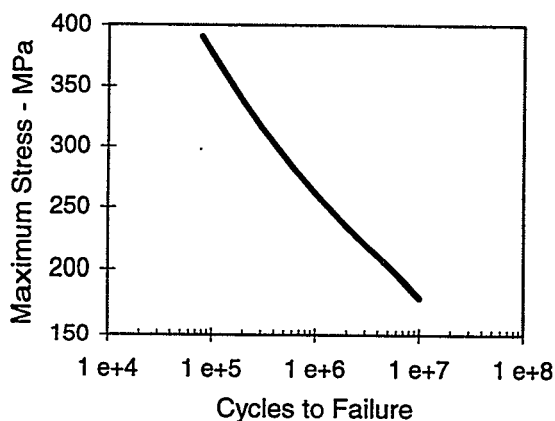


Figure 1: Power-law curve without a fatigue limit fit to cast 8630 steel S-N data. (S-N data for notched specimen subjected to R.R. Moore rotating beam tests, $K_t = 2.2$, from Steel Castings Handbook - 5th Ed., Steel Founders Society of America, 1980.)

properties for the teetering hub model are applied to CER results to allow more direct comparison of results. For this CER fatigue model, stress is calculated from flap moment using the factor 7.3 MPa/kN·m. This comparison of rigid and teetering hub fatigue loads is reviewed first.

TEETERING VS RIGID HUB

The teetering hub is designed to shed many of the cyclic forces on the blades through blade motions out of the rotor plane. In general this works well under normal operating conditions, as our fatigue analysis results demonstrate. For this comparison, both the teetering and rigid hub models are subjected to normal operating conditions and 5 extreme event scenarios to compare fatigue damage accumulation.

Ten-minute simulations of normal operating conditions were conducted at 4 wind speed intervals for the teetering hub model, and 6 intervals for the rigid hub. In addition, 5 shorter simulations were conducted using the IEC specified conditions of extreme coherent gust (ECG), extreme operating gust (EOG), extreme wind shear (EWS), extreme direction change (EDC), and extreme coherent gust with direction change (ECD) (International Electrotechnical Commission, 1994). These extreme wind conditions are specified by the IEC as ultimate load cases, but they are used in this study with a once per year recurrence rate to investigate their contribution to fatigue damage.

The fatigue damage for each wind speed interval and each of the 5 extreme conditions estimated by LIFE2 for the teetering rotor blade root are compared in Figure 2. The damage estimate for the ECD condition exceeds that for any of the normal operation wind speed intervals by several orders of magnitude. In fact, the damage estimate actually exceeds 1, implying failure even before the end of one ECD occurrence. This suggests that the ECD condition is a critical fatigue design criteria for this teetering hub turbine, although this does not imply that the teetering hub design amplifies extreme events loads. The ECD result is only indirectly a consequence of the teetering hub, and can be explained through a closer look at the model response.

The physics of the ECD condition is such that the wind direction shifts rapidly (143 degrees in 10 seconds) causing the turbine to operate upwind where the large, 7 degree pre-cone angle adds to - rather than cancels - the aerodynamic loads. The result is essentially one large cycle caused by

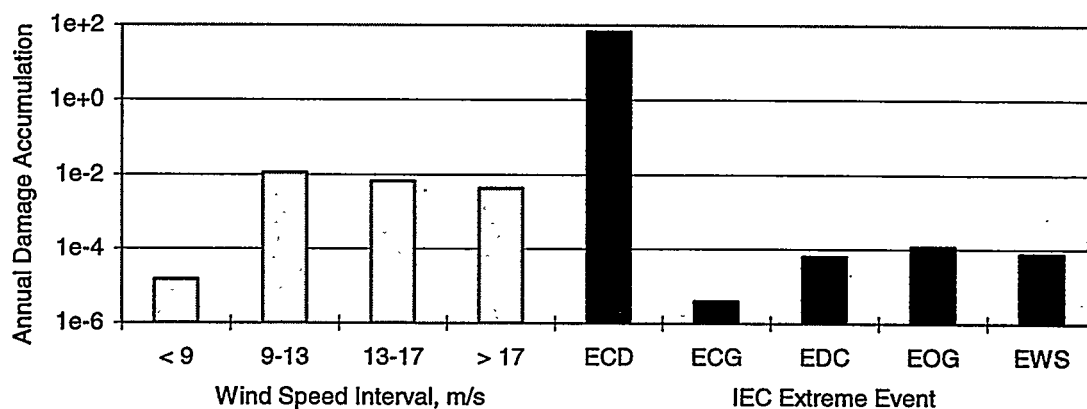


Figure 2: Fatigue damage accumulation on the teetering hub model's blade root is dominated by the IEC extreme coherent gust with direction change (ECD) event.

the change from downwind to upwind operation. Hence, the excessive damage realized during the ECD event actually results from the large pre-cone angle, and not from the teetering hub dynamics.

The results for the rigid hub CER using the same fatigue design assumptions as for the teetering hub model is shown in Figure 3. Clearly for the rigid hub CER, normal operation loads are the determining factor in fatigue life.

As mentioned above, the large damage estimate for the ECD in Figure 2 should not be interpreted to mean that the teetering rotor design amplifies extreme events. Rather, because the fatigue design criteria are based upon normal operation loads, the amount of damage indicated in Figures 2 and 3 can only be judged relative to normal operation loads. Because the teetering rotor reduces normal operation load cycles, the ECD load cycle described above is extremely large compared to the normal operation load cycles.

As an example of how well the teetering hub sheds normal operation loads as compared to the rigid hub, this fatigue design load (twice sum of average flap moment plus 4 standard deviations at 15 m/s) is compared with the IEC 1-year, extreme wind speed load. This is the flap moment experienced by a nonrotating blade in a 52.2 m/s wind speed.¹ For the rigid hub model, this load is slightly less than the fatigue design load, whereas for the teetering hub it is twice as large as the fatigue design load. This shows that the fatigue design criteria applied to the models - based on normal operation at 15 m/s - is suitable for the rigid hub CER, but far too non-conservative for the teetering hub.

RIGID HUB

In demonstrating the relative importance of extreme loads to teetering hub fatigue design, the previous discussion also demonstrated the importance of normal operation loads to rigid hub de-

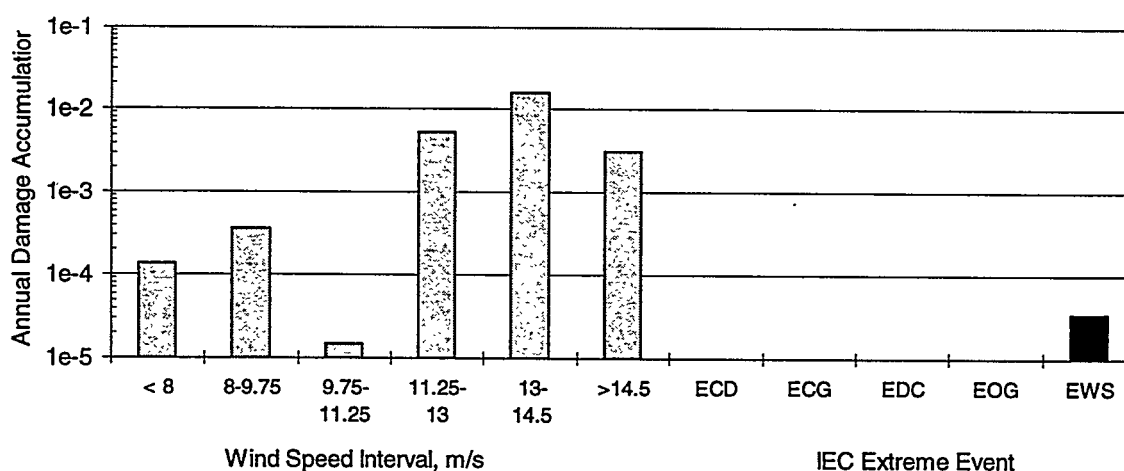


Figure 3: Unlike for the teetering hub model, fatigue damage accumulation on the CER blade root is little effected by IEC extreme events.

¹ Both models are considered stall controlled, so blades are not feathered for the hurricane gust condition.

sign. There are many sources of cyclic loads during normal operation. Results from previous CER analyses (Laino and Hansen, 1997) were analyzed to find the most damaging sources.

Gyroscopic Loads

The YawDyn model of the CER has been used in many previous studies and is well validated. Figure 4 shows that yaw dynamics predictions from this model agree well with test data. This is important in YawDyn load predictions as yaw dynamics are the source of very large load cycles. The importance of yaw motions to blade cyclic loading can be illustrated through comparison with other potential cyclic load sources. This comparison begins by using a simple model to define the relationship between yaw rate and 1P gyroscopic flap load cycles.

Considering a blade as a symmetric, slender rod rotating about one end, the flap moment amplitude, M_f , is shown to be a linear function of the yaw rate, γ' , as shown in the equation

$$M_f = 2 \cdot I_b \cdot \psi' \cdot \gamma' \quad (1)$$

where I_b is the blade flap inertia about the blade root, and ψ' is the rotor speed. For the CER, flap inertia is estimated to be $302 \text{ kg} \cdot \text{m}^2$, rotor rpm is 72, so with yaw rates as high as 20 degrees per second as indicated by test data, gyroscopic induced flap moment amplitude can reach $1600 \text{ N} \cdot \text{m}$.

Using ADAMS® to isolate several 1P load cycle sources confirms that gyroscopic load cycles are among the largest experienced by the CER. For 20 degree per second yaw rate ADAMS returns $1900 \text{ N} \cdot \text{m}$, close to theoretical prediction. For yaw error operation, the largest cycles were $850 \text{ N} \cdot \text{m}$, and for power law wind shear with exponent 0.2 flap moment amplitudes reach $450 \text{ N} \cdot \text{m}$. Thus, yaw induced gyroscopic loads are some of the largest load cycles experienced by the CER under normal operating conditions.

To see how the gyroscopic loads affect fatigue life, LIFE2 analyses were conducted on YawDyn output. Three 10-minute YawDyn simulations were conducted for each of six wind speed intervals, for a total of 18 simulations. For each wind speed interval, the three YawDyn simulations were randomly placed into one of three data groups. The use of three, randomly compiled data groups serves to avoid bias of the results toward any of the model configurations analyzed.

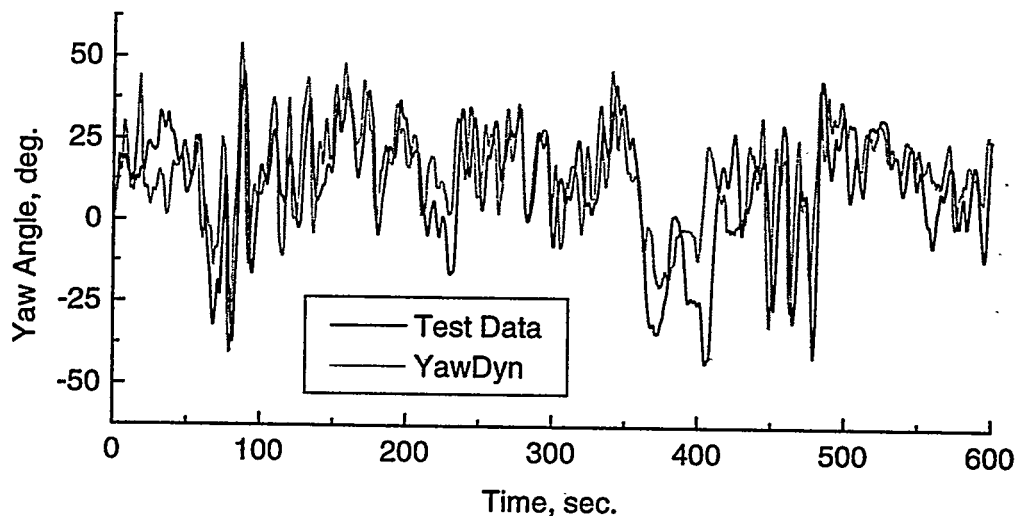


Figure 4: Comparison of yaw angle prediction from YawDyn with test data for CER.

YawDyn analyses were first conducted with the original free yaw model, attempting to imitate the test turbine response. Simulations were then repeated, this time with the model in a fixed yaw configuration; the purpose being to completely eliminate the gyroscopic loads to determine their effect on fatigue damage accumulation. The results are plotted in Figure 5.

Figure 5 shows that, although eliminating the gyroscopic loads may reduce fatigue damage substantially in some cases (Data Group I), locking the yaw introduces far more yaw error load cycles which may practically erase the benefits of reduced gyroscopic loads in other cases (Data Groups II and III).

A third set of simulations were conducted, this time allowing free yaw, but increasing the yaw damping of the model from 750 N·m·sec to 7500 N·m·sec. This is done to slow the yaw rates and thus limit the gyroscopic load cycle amplitude while preserving the benefits of free yaw operation. Figure 6 shows that increased yaw damping accomplishes this goal. Figure 7 shows that the largest stress cycles predicted with the original YawDyn model are significantly reduced with higher yaw damping. The result on fatigue life is a 12 to 20 times increase for higher yaw damping as shown in Figure 8.

Turbulence Activity

The previous exercise revealed the importance of yaw behavior to blade flap loads, and how additional yaw damping can benefit fatigue life. Another source of fatigue damage is wind turbu-

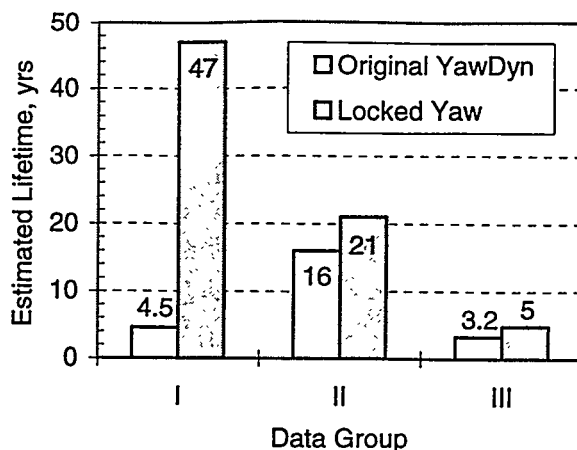


Figure 5: Comparison of LIFE2 estimates for locked and free yaw YawDyn simulations indicate that locking the yaw of the CER model does not necessarily increase fatigue life significantly.

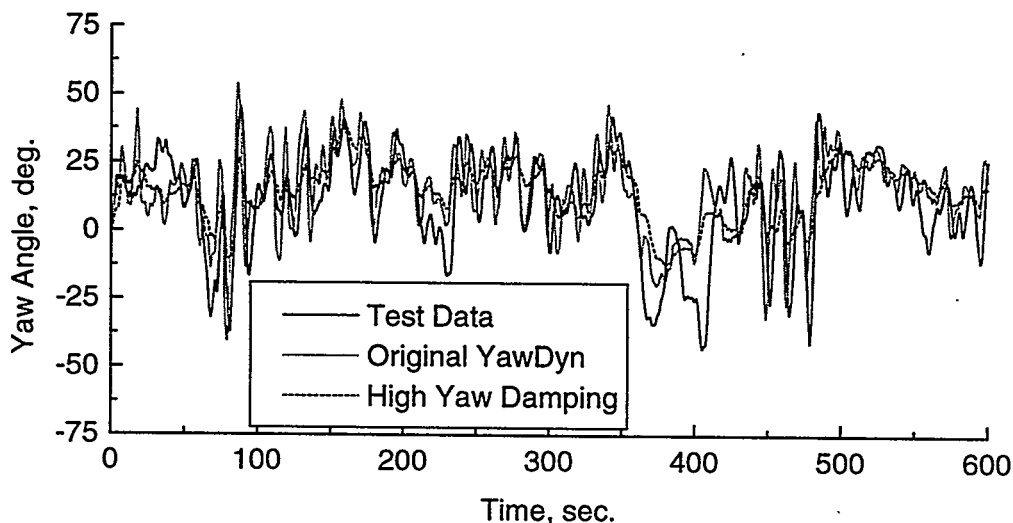


Figure 6: Comparison of yaw angle prediction from two YawDyn models with test data for CER.

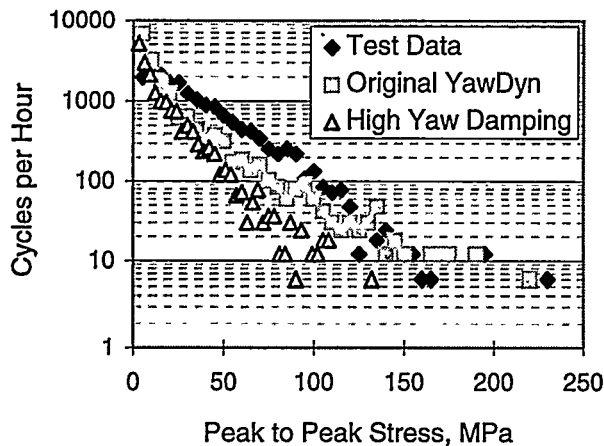


Figure 7: Rainflow cycle count-comparison of blade root stress for test data and YawDyn models with low and high yaw damping coefficients.

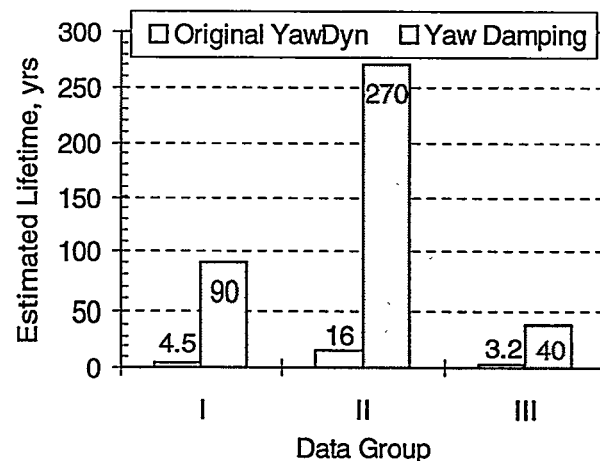


Figure 8: Increasing the yaw damping of the CER YawDyn model boosts fatigue life 12 to 20 times that of the original model.

lence. Turbulence is often thought of as *the* source of fatigue damage. While it is true that increased turbulence causes increased fatigue damage, the following discussion will reveal that the connection between the two is bridged by turbine response, and therefore the effect is not entirely uncontrollable.

The results showing gyroscopic loads as a dominant fatigue source takes on additional meaning when considering turbulence activity and its effects on turbine dynamic response. To investigate the role of turbulence on fatigue life, YawDyn simulations were conducted using simulated full-field turbulence generated by SNLWIND-3D. This permits direct control of several turbulence parameters.

Among the most sensitive of turbulence parameters is Richardson number (Ri) which is a measure of the atmospheric stability; negative Ri being unstable and positive Ri , stable. In general, turbulence activity increases with decreasing atmospheric stability. Conducting YawDyn and subsequent LIFE2 analyses for three different stability conditions demonstrated how sensitive turbine fatigue loading is to turbulence activity. For Richardson numbers of 0.1, 0.0, and -0.1 - yielding turbulence intensities of 8%, 14%, and 21%, respectively - the results from the fatigue analyses are shown in Figure 9. Note the trend follows that expected for the turbulence intensity values.

It turns out, however, that the relative difference between estimated fatigue life for unstable and stable turbulence need not be so dramatic. The increased turbulence intensity

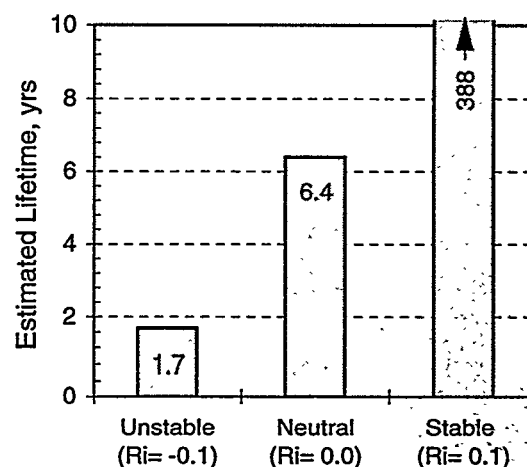


Figure 9: Estimated fatigue life for CER YawDyn model in 3 different turbulence conditions. Turbulence for YawDyn was generated by SNLWIND-3D.

associated with unstable conditions causes more active wind direction and shears, leading in turn to greater yaw activity as shown in Figure 10. The gyroscopic loads from this increased yaw activity have previously been shown to be the major culprit of fatigue damage. Hence, increasing the yaw damping also increases the CER's ability to withstand more active turbulence.

CONCLUSIONS

Fatigue analyses of passive yaw wind turbines have been performed revealing several important factors regarding fatigue damage sources. Among these is that the teetering hub's ability to reduce normal operation loads makes extreme wind conditions a critical aspect in fatigue design of the teetering rotor blades. The hurricane gust condition is commonly assessed on all turbine designs as an ultimate load scenario. The results shown here indicate it may also be a useful fatigue design criteria for teetering rotors, and possibly rigid hub rotors as well.

Analysis of the rigid yaw CER revealed that yaw rates induce gyroscopic load cycles with potentially some of the largest amplitudes experienced by the machine. This finding may be important to not just down wind, rigid hub turbines, but smaller tail vane machines as well. Increasing yaw damping was shown to be effective for reducing these gyroscopic loads and significantly increasing fatigue life.

Increasing yaw damping also reduces susceptibility to turbulence induced load cycles, which result from increased yaw rates due to more active wind direction and shear changes. This makes the machine more tolerant of sites with greater turbulence intensity; sites that might otherwise be detrimental to operation without any yaw damping.

The fact that turbulence intensity, and hence fatigue damage, is greatest under unstable atmospheric conditions is important to fatigue design standards. The current IEC standards specify neutral conditions, but results shown here indicate this specification may not be conservative enough.

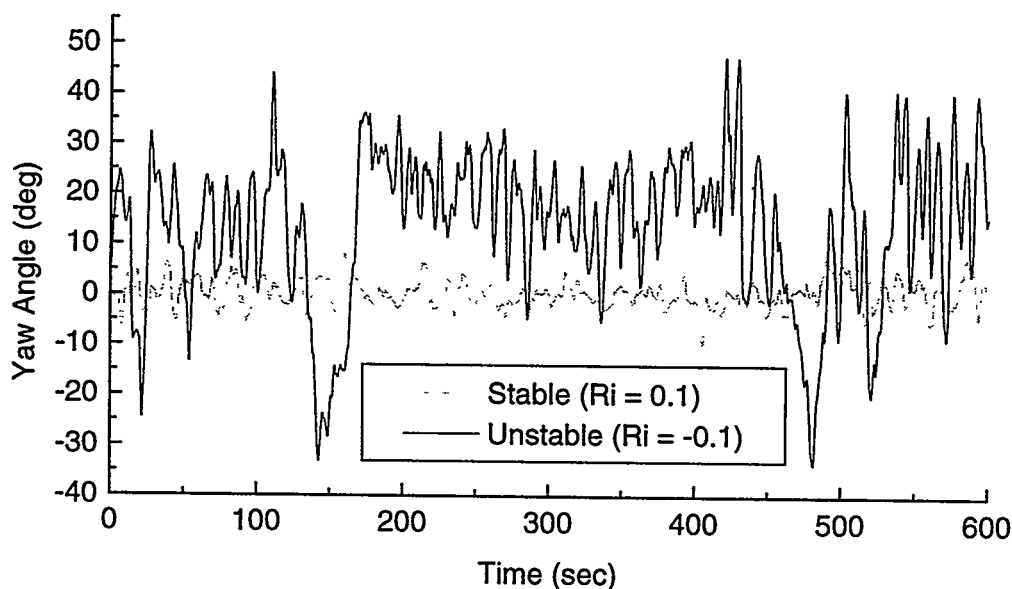


Figure 10: Stable atmospheric conditions cause fewer wind direction changes and less severe wind shears than unstable conditions, leading in turn to less active wind turbine yaw motion. Data taken from CER YawDyn model simulations using simulated full-field turbulence.

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INVESTIGATION OF LOAD REDUCTION FOR A VARIABLE SPEED, VARIABLE PITCH, AND VARIABLE CONING WIND TURBINE

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ABSTRACT

A two bladed, variable speed and variable pitch wind turbine was modeled using ADAMS[®] to evaluate loads reduction abilities of a variable coning configuration as compared to a teetered rotor, and also to evaluate control methods. The basic dynamic behavior of the variable coning turbine was investigated and compared to the teetered rotor under constant wind conditions as well as turbulent wind conditions. Results indicate the variable coning rotor has larger flap oscillation amplitudes and much lower root flap bending moments than the teetered rotor.

Three methods of control were evaluated for turbulent wind simulations. These were a standard IPD control method, a generalized predictive control method, and a bias estimate control method. Each control method was evaluated for both the variable coning configuration and the teetered configuration. The ability of the different control methods to maintain the rotor speed near the desired set point is evaluated from the RMS error of rotor speed. The activity of the control system is evaluated from cycles per second of the blade pitch angle. All three of the methods were found to produce similar results for the variable coning rotor and the teetered rotor, as well as similar results to each other.

INTRODUCTION

At the University of Utah, under contract from the National Renewable Energy Laboratory (NREL) we are continuing to make improvements in the capability to model wind turbine control systems. This ability is needed due to the increasing complexity of wind turbines and controls for these systems. Modeling of control systems in wind turbine design codes allows the testing of many configurations in less time than would otherwise be feasible. It is possible to model digital or continuous control systems and actuator dynamics with the turbine structural dynamics and aerodynamics to determine performance and effects on complete system dynamics.

As a further investigation into the ability to model and control complex systems, an ADAMS[®] model is used to investigate the loads and control of a two bladed, variable speed, variable pitch, and variable coning wind turbine. Loads and control of the variable coning rotor is compared to a similar turbine with a teetered rotor. Variable coning of the blades is investigated as a means to reduce blade loads.

TURBINE MODEL AND DYNAMICS

The model used in this study is a two bladed, variable speed, variable pitch turbine. It operates down wind in free yaw. The model is implemented in ADAMS[®] linked with AeroDyn [Hansen, 1996]. Two configurations of this basic model were studied. The first model has a variable coning rotor and the second has a teetered rotor with a fixed cone angle of 3.5 degrees. The models have rigid towers and rigid blades. This produced three degrees of freedom for the teetered model: rotor speed, teeter, and yaw. For the variable coning model each blade flaps independently producing 4 degrees of freedom: rotor speed, blade 1 flap, blade 2 flap, and yaw.

There are two regions of operation for a variable speed, variable pitch wind turbine. In low winds the generator torque is regulated to allow the turbine to operate at the optimum tip speed ratio, with the blades maintained at a constant pitch angle. In high winds the blades are controlled in pitch to maintain the rotor near constant speed. For the current model, the generator operates at constant torque for high winds. A set point of 85 rpm was used in all simulations, with a resulting power output of 250 kW.

For the variable coning turbine it is necessary to determine what value is desired for the cone angle as a function of wind speed, rotor speed, blade loads, etc. The purpose of variable coning is to reduce the blade flap moments to some lesser value than would be obtained for a fixed cone angle rotor. The equivalent question then is what value is desired for the flap moments. The lowest value obtainable is zero, and this was the value chosen for this study. Thus, in normal operation each blade flaps freely and independently. A cone actuator is included in the model, which produces a moment between the two blades. The purpose of the actuator is to maintain tower clearance. Under normal operation no moment is applied. If the cone angle becomes too low, indicating the blades are getting close to the tower, a moment is applied to increase the cone angle. The moment applied between the two blades is a linear function of the cone angle, starting at zero degrees. What is referred to as cone angle in this study is the average value of flap angle for the two blades. The blades are at zero flap angle when perpendicular to the low speed shaft, with positive flap in the down wind direction. Stops on each blade are included in the model to ensure that the blades do not hit the tower. Stops are also included for the teetered rotor to maintain tower clearance.

To investigate dynamics of the two configurations constant wind with a 1/7 power law vertical shear was used as input to the models. Loads and deflections for the variable coning turbine are compared to the teetered turbine. The cone angle, for the variable coning rotor, and root flap moment, for the teetered rotor, as a function of wind speed are shown in Figure 1. For the variable coning rotor, the cone angle is nearly constant below the power regulation region (wind speeds less than 13 m/s). In the power regulation region the cone angle decreases with increasing wind speed. This is due to pitching of the blades, which results in lower lift on the outboard blade sections. In very high winds the lift on the outboard sections becomes negative. For the teetered model the root flap bending moment increases up to the power regulation region, then decreases, and becomes negative for high winds. This is again due to lower or negative lift on the outboard blade sections.

Flap angle and teeter angle as a function of time at 10 m/s wind speed are shown in Figure 2. As can be seen in the figure each blade of the variable coning rotor undergoes a once-per-revolution teeter type motion. At this wind speed the flap oscillations are slightly larger than the teeter oscillations. Flap and teeter oscillation amplitude as a function of wind speed is shown in Figure 3. The flap amplitude is seen to be larger than the teeter amplitude for wind speeds below power regulation. This is partially due to one

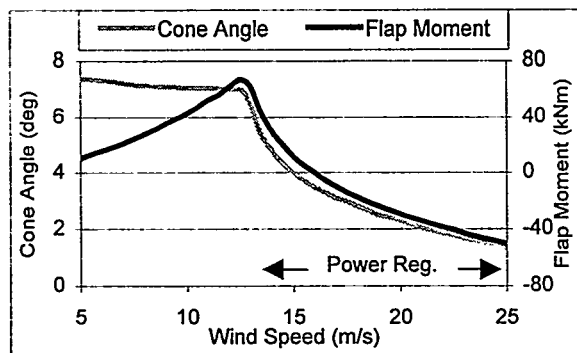


FIGURE 1: CONE ANGLE AND FLAP MOMENT VERSUS WIND SPEED.

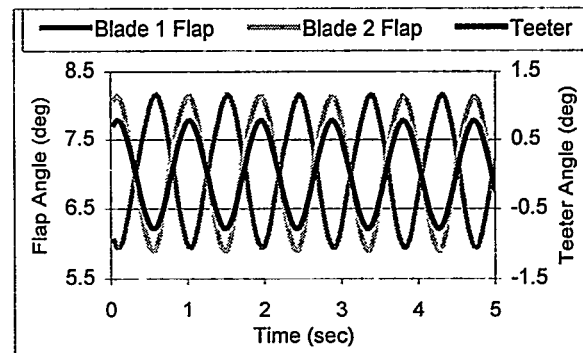


FIGURE 2: BLADE FLAP AND TEETER COMPARISON. 10 M/S WIND SPEED.

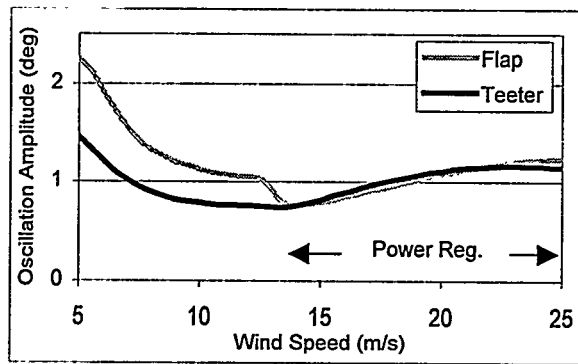


FIGURE 3: FLAP AND TEETER AMPITUDE VERSUS WIND SPEED.

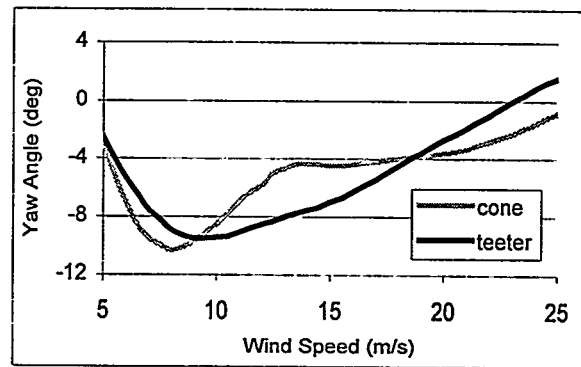


FIGURE 4: YAW ANGLE VERSUS WIND SPEED.

blade of the teetered rotor having a lower portion of its length stalled, providing more aerodynamic damping. The yaw behavior of the two models is also somewhat different which may also contribute to the difference in amplitude behavior. The yaw angle as a function of wind speed is shown in Figure 4. As seen in Figure 3 the amplitude of oscillation is high for low wind speeds, due to the low dynamic pressure. The amplitude then decreases as the wind speed and rotor speed increase, increasing the dynamic pressure seen by the blades. In high winds the amplitude of oscillation again begins to increase as the variation of wind speed across the rotor increases.

CONTROL METHODS

Three methods of control were studied for both the teetered turbine and the variable coning turbine. These control methods are, an integral, proportional, and derivative (IPD) control system, an adaptive control method termed generalized predictive control (GPC), and a bias estimation model (BM) control system. The variable to be controlled was the turbine speed. All of the control systems are digital systems sampled at 25 Hz. Kaimal turbulence generated by SNLWind -3D [Kelly 1993], as specified by the IEC [International Electrotechnical Commission, 1994], is used for wind input to evaluate performance of the different control systems.

IPD Control

The first method studied was an IPD control system [Ogata, 1993]. For this control system the proportional term is implemented in velocity form. The velocity form of the proportional term increases damping of the system, and is not as sensitive to noise as the derivative term. Therefore, a lower gain can be used on the derivative term. This is a standard method, and is included as a baseline to determine if significant improvement is obtained from more complex control methods.

Generalized Predictive Control

Generalized predictive control [Clarke et al. 1987] is an adaptive control method where estimates of future outputs of the plant are used to calculate the current control signal. The model of the turbine used for the method is shown in Figure 5, where p is the blade pitch angle, v is the hub height wind speed, and rpm is the rotor speed. The coefficients of the model are adapted using a recursive least squares filter. This simple model of the turbine

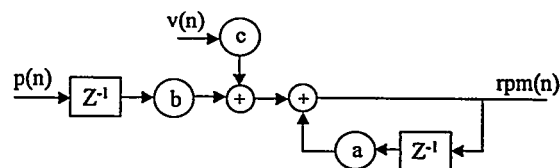


FIGURE 5: TURBINE MODEL.

was found to produce an accurate prediction of rotor speed, with nearly stationary coefficients. More complex models were tried but they did not improve the estimate of rotor speed.

The equations for generalized predictive control of order three for the model shown are given by

$$R = GP + HV + F$$

Where

$$R = \begin{pmatrix} rpm(n+1) \\ rpm(n+2) \\ rpm(n+3) \end{pmatrix} \quad P = \begin{pmatrix} p(n) \\ p(n+1) \\ p(n+2) \end{pmatrix} \quad V = \begin{pmatrix} v(n) \\ v(n+1) \\ v(n+2) \end{pmatrix}$$

$$G = \begin{bmatrix} c & 0 & 0 \\ ac & c & 0 \\ a^2c & ac & c \end{bmatrix} \quad H = \begin{bmatrix} b & 0 & 0 \\ ab & b & 0 \\ a^2b & ab & b \end{bmatrix} \quad F = \begin{pmatrix} a \\ a^2 \\ a^3 \end{pmatrix} rpm(n)$$

Using the cost function

$$J = \|R - R_D\|^2 + \sigma \|P\|^2$$

where R_D is the desired rpm, and σ is the decision factor, which weighs the use of control against the error in rpm. R_D is known for all time since the desired rotor speed is a constant in the power regulation region. This cost function produces the control law

$$P = [\sigma I + G^T G]^{-1} G^T [R_D - HV - F]$$

The control law has an additional term HV as compared to the standard form of the generalized predictive controller due to the additional wind input. V contains the current value of wind speed and future values of the wind speed. To predict these future wind speed values an additional recursive least squares filter was used to estimate the current wind speed from the three previous values. The adapted coefficients from the filter were then used to predict the future values.

This control method has only one parameter to adjust, σ , and has the ability to adjust the control as the turbine parameters vary with changing conditions. It is also possible to include actuator dynamics in the equations for the system. One difficulty with this method is that larger values of the decision factor result in a steady state error. To eliminate this steady state error an integrator was added to the control system. The integrator had a very low gain, which contributed little to the dynamics of the system.

Bias Estimation Model

For the bias estimation model [Franklin et al. 1990] a linear model of the turbine was used in the estimator. The same basic model of the turbine used in the generalized predictive control without the wind input was used as the linear model. An average value of the coefficients a , and b for 18 m/s average wind speed were used. The estimator is augmented with an additional equation which estimates unmodeled disturbances acting on the system, which for this case is the effect of the wind on the turbine. This estimate of the disturbance is included in the control law to cancel out the disturbance. Again low gains resulted in a steady state error of rpm, therefore, an integrator with low gain, as in the GPC, was added to the system.

RESULTS

Comparisons of the three control methods for turbulence simulations at average wind speeds of 15, 18, and 21 m/s are shown in Tables 1 and 2, for the teetered rotor and the variable coning rotor respectively. Shown in the tables is RMS error of rotor speed and pitch cycles per second for the three methods. The

TABLE 1: TEETERED ROTOR CONTROL METHOD COMPARISON

Wind Speed	15 m/s		18 m/s		21 m/s	
	RMS Rotor Speed Error	Pitch Cycles/sec	RMS Rotor Speed Error	Pitch Cycles/sec	RMS Rotor Speed Error	Pitch Cycles/sec
IPD	6.52	0.090	5.51	0.103	4.98	0.120
GPC	7.56	0.052	5.08	0.102	3.88	0.122
BM	6.79	0.102	5.10	0.118	4.52	0.137

TABLE 2: VARIABLE CONING ROTOR CONTROL METHOD COMPARISON

Wind Speed	15 m/s		18 m/s		21 m/s	
	RMS Rotor Speed Error	Pitch Cycles/sec	RMS Rotor Speed Error	Pitch Cycles/sec	RMS Rotor Speed Error	Pitch Cycles/sec
IPD	6.49	0.092	5.54	0.103	5.01	0.122
GPC	7.65	0.053	5.14	0.102	3.97	0.123
BM	6.69	0.100	5.13	0.120	4.60	0.147

RMS error of rotor speed indicates how well the control system was able to maintain the rotor speed near the desired value. The blade pitch cycles per second indicates the activity of the control system.

All of the control methods performed very similarly for both the teetered rotor and the variable coning rotor. Also, all of the control methods performed similarly to each other. The RMS error decreases with increasing wind speed for all of the methods. This is due to the increase in gain of the blade pitch, that is at higher wind speeds there is a greater change in rpm for a given change in blade pitch. The GPC has a lower error for the two higher wind speeds with nearly the same number of blade pitch cycles. However, the GPC had the greatest change in RMS error for the three wind speeds. From these simulations it is not possible to state that one method would be preferred over another. Different wind conditions, turbine dynamics, or additional factors not considered here might make one method more applicable in comparison to the others.

Four minutes of time series results from 18 m/s turbulence simulations are shown in Figures 6-9. These plots are for the IPD control system. As mentioned previously the results are very similar for all of the control methods. Rotor rpm and blade pitch is shown in Figure 6. There is a trade-off between the amount of pitch actuation and the variation of rotor speed. The control methods were all tuned to have a variation in rotor speed of approximately +10 to -10 rpm from the set point of 85 rpm. The resulting variation in power as well as hub height wind speed for the simulation is shown in Figure 7. The variation in power was thought to be reasonable, but could be reduced by increasing the blade pitch control system gains. The cone angle for the simulation is shown in Figure 8. The cone angle is somewhat active but not unreasonable. It is seen to follow the wind speed, with higher cone angles for lower wind speeds and lower cone angles for higher wind speeds. The root flap bending moment for both the variable coning rotor and teetered rotor for the same time series is shown in Figure 9. The flap moment is seen to be essentially zero for the variable coning rotor, while the flap moment for the teetered rotor follows the same pattern as the cone angle for the variable coning rotor. Thus, it can be seen that the blade loading goes either into blade motions for the variable coning rotor, or flap loads for the teetered rotor.

Comparisons between motions and loads as a function of wind speed for turbulence simulations and constant wind simulations are shown in Figures 10-13. Turbulence simulations were run for average wind speeds of 7, 11, 15, 18, and 21 m/s. Included in the figures are the average values, maximum

values, minimum values (where appropriate), and 3 standard deviations for the simulations. Figure 10 is a plot of flap oscillation amplitude versus average wind speed for the coning rotor. Figure 11 is a plot of teeter oscillation amplitude versus wind speed for the teetered rotor. The average values of oscillation are seen to be higher for both models in the turbulent wind, as would be expected. However, the increase in amplitude, both the average and the maximum value, is greater for the variable coning rotor. The lower amplitude for the teetered rotor seems to be due to the another blade having different wind conditions.

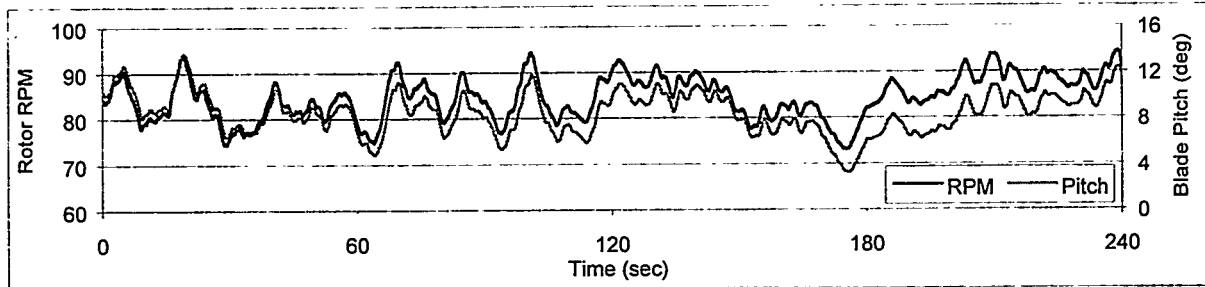


FIGURE 6: ROTOR SPEED AND BLADE PITCH VERSUS TIME.

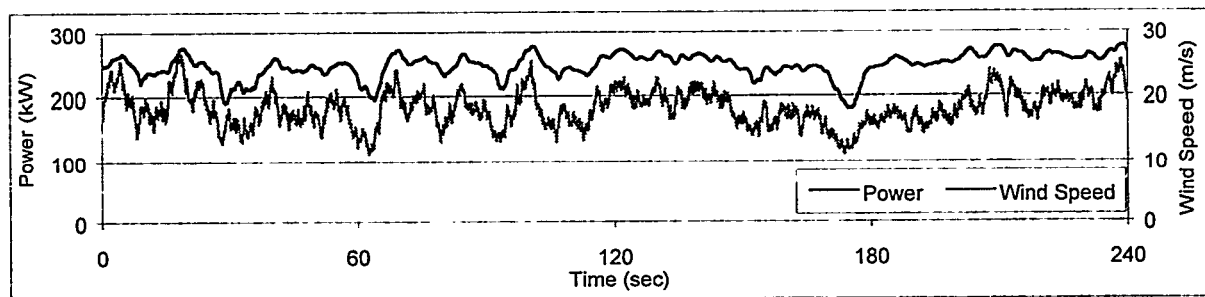


FIGURE 7: POWER AND WIND SPEED VERSUS TIME.

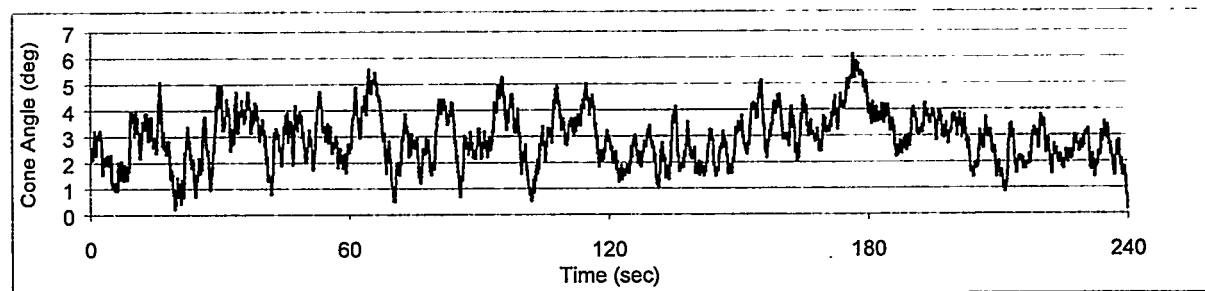


FIGURE 8: CONE ANGLE VERSUS TIME.

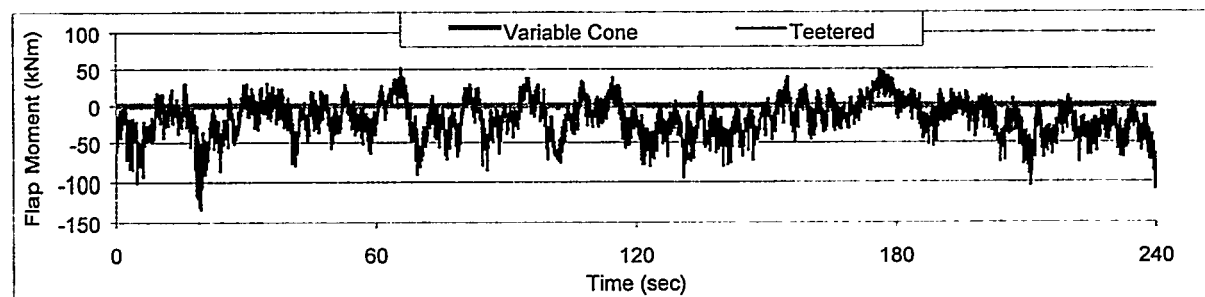


FIGURE 9: ROOT FLAP BENDING MOMENT VERSUS TIME.

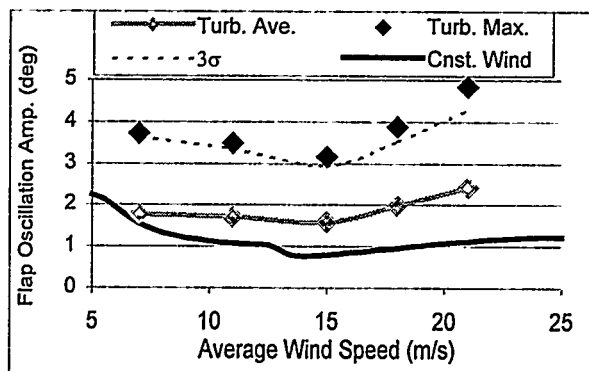


FIGURE 10: FLAP OSCILLATION AMPLITUDE VERSUS WIND SPEED.

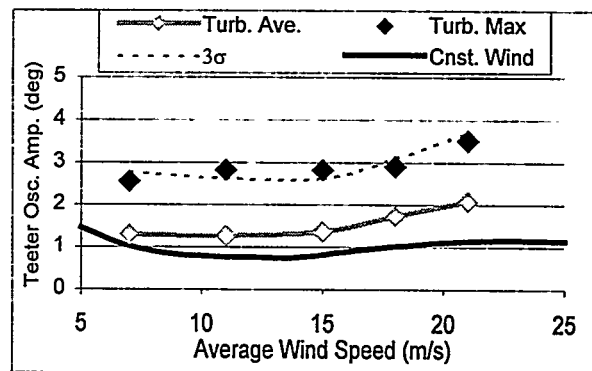


FIGURE 11: TEETER OSCILLATION AMPLITUDE VERSUS WIND SPEED.

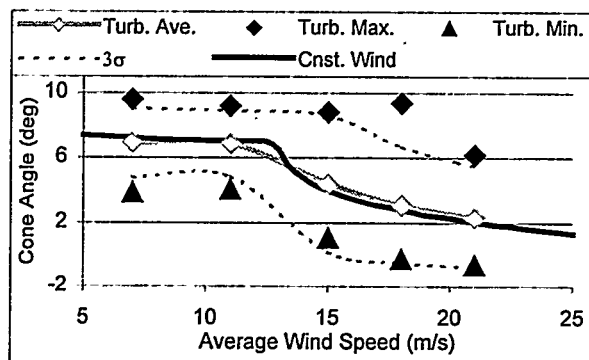


FIGURE 12: CONE ANGLE VERSUS WIND SPEED.

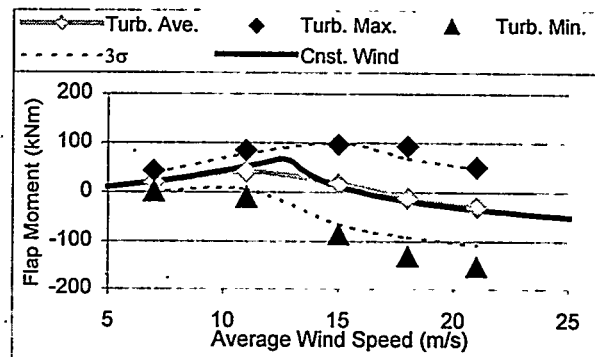


FIGURE 13: FLAP MOMENT VERSUS WIND SPEED.

The cone angle as a function of wind speed is shown in Figure 12. The average value follows that for the constant wind speed simulations. The maximum and minimum values seem reasonable, and the variation does not seem to be increasing considerably with increasing wind speed. Figure 13 is a plot of flap moment versus wind speed for the teetered rotor. The average flap moment is also seen to follow the values obtained for constant wind simulations. The variation in flap moment increases for the lower wind speeds but seems nearly constant for the three higher wind speeds. The flap moment for the variable coning rotor was low in comparison to the teetered rotor. The maximum absolute value of flap moment in any of the variable coning simulations was -13 kNm, with a minimum flap angle of -2.8 degrees. The blade would strike the tower at approximately -10 degrees flap for this model. The blades of the variable coning rotor did not hit the stops, which would have increased the maximum flap moment. The stops for the variable coning rotor begin at -3.5 degrees. The teetered rotor also did not hit the stops, which begin at 3.5 degrees of teeter.

CONCLUSIONS

The dynamics of the two rotor configurations were found to be reasonable for the simple models studied. Both models behaved well in low wind speed, low rotor speed operation, when the dynamic pressure is low resulting in lower damping. They were also quite well behaved in high winds. Flap angle oscillations for the variable coning rotor are larger than those for the teetered rotor, although the flap moments are considerably larger for the teetered rotor. Just as there is a trade off between pitch activity and how tightly the rotor speed is held constant, there is a trade-off between blade flap motions and blade flap moments.

The three control methods studied produced similar results for both of the rotor configurations studied. The RMS error of rpm, as well as the number of blade pitch cycles per second is nearly identical for the variable coning rotor and the teetered rotor. The three control methods produced reasonable variation in rotor speed, and all of the methods performed similarly. It is not possible to state that one method would be preferred over another. For this model it seems that there is little to be gained by increasing the complexity of the control method.

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An Interactive Version of PropID for the Aerodynamic Design of Horizontal Axis Wind Turbines

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Abstract

The original PROP code developed by AeroVironment, Inc. and its various versions have been in use for wind turbine performance predictions for over ten years. Due to its simplicity, rapid execution times and relatively accurate predictions, it has become an industry standard in the US. The Europeans have similar blade-element/momentum methods in use for design. Over the years, PROP has continued to be improved (in its accuracy and capability), e.g., PROPSH, PROPPC, PROP93, and PropID. The latter version incorporates a unique inverse design capability that allows the user to specify the desired aerodynamic characteristics from which the corresponding blade geometry is determined. Through this approach, tedious efforts related to manually adjusting the chord, twist, pitch and rpm to achieve desired aerodynamic/performance characteristics can be avoided, thereby making it possible to perform more extensive trade studies in an effort to optimize performance. Past versions of PropID did not have supporting graphics software. The more current version to be discussed includes a Matlab-based graphical user interface (GUI) and additional features that will be discussed in this paper.

Introduction

In recent years a new code, PropID (pronounced "Prop-I-D"), for horizontal axis wind turbine performance prediction has been under development at the University of Illinois at Urbana-Champaign. The unique strength of the current design method is its inverse design capability. For instance, the method allows the designer to specify directly the peak power for a stall-regulated rotor. The iterative inverse solver is then used to appropriately modify the blade design so that the desired peak rotor power is achieved. More generally, the method permits the designer to specify several performance characteristics that are achieved automatically by iteration on the blade geometry and operating conditions. The design methodology used in the code is similar to that developed for inverse airfoil and cascade design.^{1,2}

PropID not only allows for the specification of single variables, such as the peak power, but it also allows for the specification of distributions, such as the blade lift distribution and/or axial interference factor distribution. Such distributions are achievable as long as the blade twist and/or chord distributions are left

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to be determined by the method.

PropID also has multipoint design capabilities. For example, the blade lift coefficient distribution can be prescribed for one condition while the axial induction factor distribution can simultaneously be prescribed for a different condition. In addition, the designer can simultaneously specify the peak rotor power constraint, which may correspond to yet another condition.

The analysis routines included in PropID are those used in the PROP code, the earliest version of which was developed nearly two decades ago.^{3, 4, 5, 6} After various improvements,^{7, 8, 9} including a post-stall airfoil performance synthesization method for better peak power prediction at high wind speed,^{10, 11, 12, 13} the performance prediction methodology of PROP has become an industry standard. Although discrepancies between field tests and predictions have been documented and discussed, the PROP analysis method (based on blade element/momentum theory) has proved to be invaluable as a guide to the design of a series of successful wind turbine blade designs.

A shortcoming of PROP that was carried over into the first version of PropID was the lack of graphics routines for visualization of the resulting performance predictions. Rapid and interactive viewing of the data is a key element to making PropID more user friendly. A new graphical user interface (GUI) to PropID is discussed in this paper.

Another shortcoming of PROP is the fixed-format input-file structure, which in general is not user friendly. To avoid the difficulties inherent to a fixed-format input-file structure, PropID is a keyword-based code; that is, the input file is a free-format script-type file that contains a journal of commands for either batch mode execution or interactive use. The new input file format is also discussed in the current paper.

PropID was originally written in FORTRAN and many hours of labor have gone into its design. However, as mentioned, the ability to graphically display results is an important and needed feature. To rewrite the code to include graphics would be impractical and too time consuming. Moreover, it is desirable to keep PropID and the graphical post-processor code platform independent so that the user can run the code on any computer ranging from a PC, UNIX workstation or even a supercomputer. The FORTRAN code was written in standard ANSI FORTRAN 77 and is portable to practically any platform. Unfortunately, with respect to graphical output, most programming languages are very platform specific. This ultimately determined which language or software would be used to develop the PropID GUI. Because Matlab is available for a wide range of computer platforms and is platform independent (including its graphical abilities) it was decided to retain all the original FORTRAN PropID code and develop a separate graphical post-processor written in Matlab. Matlab code is typically quite small and compact yet powerful and has a rich set of features and functionality.

General Features and Philosophy

Several of the features in the basic PROP code have been enhanced in PropID. For instance, with the PROP code, airfoil data is included in the input file for each of the equidistant stations along the blade. Only one set of C_l - C_d data can be given per station, so the effects of Reynolds number cannot be readily considered. Also, a change in the distribution of airfoils along the blade span is quite tedious, since new data for each station must be generated to replace the old. In PropID, the approach is simply to specify the airfoils used and their corresponding locations. To determine the corresponding airfoil performance data at a given blade element station (which may or may not correspond to a specific airfoil), a three-dimensional interpolation is performed on the bounding airfoils, the Reynolds number, and angle of attack. Thus, changing the

distribution of airfoils is straightforward and only involves modifying a few lines rather than the entire airfoil data table used in PROP.

In PropID, the chord and twist distributions can be given at selected points that do not necessarily fall on those equidistant points spaced along the blade span for performance calculations. From the specified points, the corresponding chord and twist for each blade element are determined by splining the given data. This is an improvement over PROP in which the chord and twist distributions must be specified for each blade element. Thus, in the current implementation, the specified chord and twist distributions are independent from the number of blade elements. In this case, increasing the number of elements used in the performance calculations is readily accomplished.

Most users prefer to work within a graphical user interface (or GUI). Although this is usually a more user-friendly environment there are also disadvantages associated with a GUI. One disadvantage typically associated with a pure GUI environment is a dynamic input. The input parameters usually are restricted to those which are predefined in the GUI dialog boxes and windows. Usually the user cannot add or remove any fields or parameters. On the other hand, a simple or basic scripting language will allow the user to enter an unlimited number of input variables and parameters. Also a scripting language is not confined to the predefined entities in the GUI environment. Thus, the possible permutations and combinations are endless. To retain the power and flexibility of dynamic input, the authors have opted to retain the text-based input format (scripting) to PropID while developing the new graphical output features.

From the user's perspective, the ability to rapidly view results from case to case through a GUI is much more appealing than tediously importing ASCII files of tabulated data into a post-processor plotting package, as is often done using spreadsheet software. This was the prime motive for adopting the GUI environment. Also, another important aspect of any GUI for design is to have the ability to view several past cases simultaneously (the history of the design), in addition to reference cases for comparison. This feature has been included in the new GUI as well. Finally, it is important to ensure that within the GUI environment the user is not bound by a predefined set of output styles and options such as, line types, colors, numbers of past cases, reference cases, etc. This flexibility is also maintained in the new PropID GUI.

Standard ASCII text files are used for input throughout PropID with both the FORTRAN and Matlab code. This gives the user the ability to use a standard text editor to easily create or modify PropID input files and Matlab-GUI configuration settings. A simple input format is used consisting of keywords and a value or set of values. Examples are shown in the next section.

Software Capabilities and GUI Interface

Working Overview

The PropID/Matlab software suite is run entirely from within the Matlab GUI interface. Upon first execution of the application, some files will automatically be created to store the user preferences and current settings. There are three main sections to the application: 1) interactive analysis and graphical display of results, 2) utilities, and 3) customization and user settings. Most of the user's time will be spent in the interactive analysis and graphical display section.

During execution of the FORTRAN analysis code, the user has a choice of either running the code interactively, by inputting keywords and their values from a command-line prompt, or by creating an input

```

! This is a remark - input data file
MODE 1.0          ! wind turbine mode
LTIP 1.0          ! use tip loss model
LHUB 1.0          ! use hub loss model
...
CH_TW
    0.197246      26.0000
...
AIRFOIL_MODE      1
    1.0           16.0       19.0
    -5.000        -0.057
...
NEWT2SDDP 100 9 10 8 2
1  -0.0450
2  -0.0880
1 1 2  2 100 2 0.003
...
*
```

Figure 1. A portion of a PropID input file.

```

OS NT
DialogForeground 'g'
PushBackground [0.5 0.5 0.5]
...
```

Figure 2. Part of the PROPID.DAT file used as input to the Matlab GUI interface.

file containing the desired inputs and running the code in batch mode. Execution of the analysis code generates output files, such as the power curve, lift coefficient distribution, etc. These files are read by the graphical post-processor. Results from each design case (after each run or design analysis) are automatically saved in a case history folder and previous design cases are moved one generation down. The last five cases are stored. This feature can be used to display and compare up to four previous design cases with the most recent case and to evaluate if the current design is better or worse than any of the previous cases. Any one of the last five cases can be restored and used as the basis for the next analysis run. Another feature allows for any one design case to be used as a reference. If selected, the reference case will always be displayed against the current cases and will not “age” as the other design cases do.

Up to six different graphs with user selected data (each containing up to five cases from past runs as well as the reference case) can be displayed on individual windows and/or all together in a single summary window. The summary window allows the user to get a quick overview of the design session, while the larger individual window can be used for closer inspection.

The user can customize which graphs are to be displayed and also define which line type and color are to be used for the different cases. Once set, these options remain in effect until the user changes them again. Several different customized settings (or “preferences”) can be saved to disk and restored at any time. Thus, it is possible for a user(s) to define many different “views” which can be recalled at any desired point.

Typical Input Files and Formats

Figure 1 shows a small portion of a typical input to the PropID FORTRAN code. It consists of a keyword and a value or set of values. An exclamation mark (“!”) denotes that the remainder of the line is to be ignored, i.e. a comment. An asterisk (“*”) is used to specify the end of input for both batch and interactive modes. An input file can be created which consists of many keywords and their corresponding values. The FORTRAN code reads and processes the input lines sequentially, some lines providing input, while others provide initial calculations or user input from terminal.

A second file (PROPID.DAT) shown in Fig. 2 is used to customize the GUI interface in the Matlab

```

"filename"      "Graph Title"    "xlabel"      "ylabel"
"fort095.dat"  "Chord vs Radius" "Radius (ft)" "Chord (ft)"
...

```

Figure 3. Part of the GRAPH.DAT file used as input to the GUI interface and set graphing options.

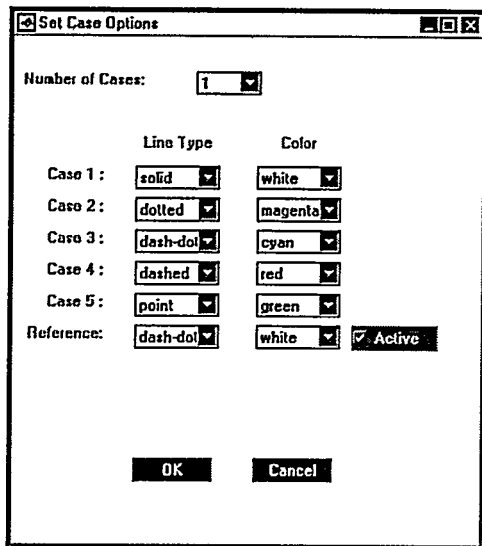


Figure 4. The GUI dialog box for setting the case options for line style and for color.

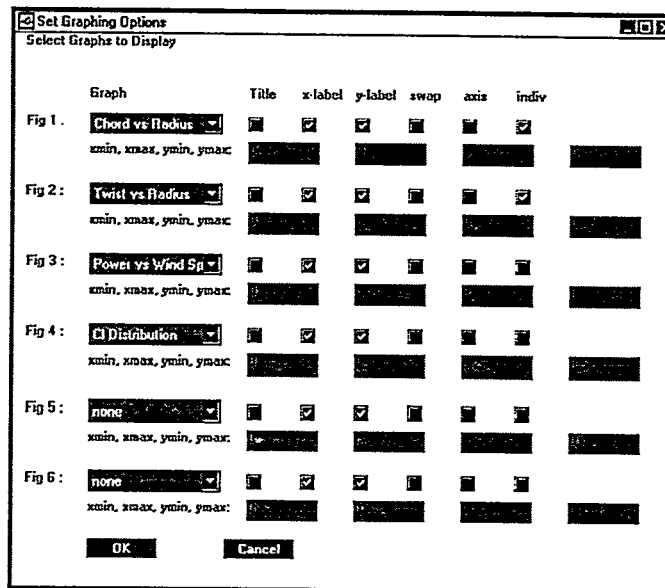


Figure 5. The GUI dialog box for setting graphing options such as plot type, graph title, x and y axis labels, axes limits and individual plots.

environment. The first line of this file is required. It defines the operating system on which the application is executed (Unix, NT, Windows 95, Mac, and many more). The remainder of the file is optional and if not specified the default settings will be used. This file can be used to define the color (foreground and background) of the windows, dialog boxes, text strings, input fields, push buttons and pull-down menus.

The remaining required file shown in Fig. 3 is GRAPH.DAT, which is used to define the output files that are generated by the FORTRAN analysis code. The file consists of multiple entries, each defining the name of an output-input file, a graph title, x-axis and y-axis label.

PropID GUI Environment and Output

Figure 4 shows the dialog that is used to define the options for displaying the cases. A user can specify the number of past cases to be displayed on an active graph, as well as the line type and color for each individual case. The reference option is to specify if a reference case should be used and its line type and color options. If selected, the reference case will always be graphed and will not "age." The color and style of this dialog and others is specified in the PROPID.DAT data file.

Figure 5 shows the dialog for setting the individual graph (plots) options. The user can specify whether to display a graph title (heading) and x-axis and y-axis labels. Additional parameters specify whether to swap the x and y data when reading in the ASCII file, maintain axes aspect ratio and whether to display a graph in its own individual window. By default, every graph selected to be displayed will be plotted in the

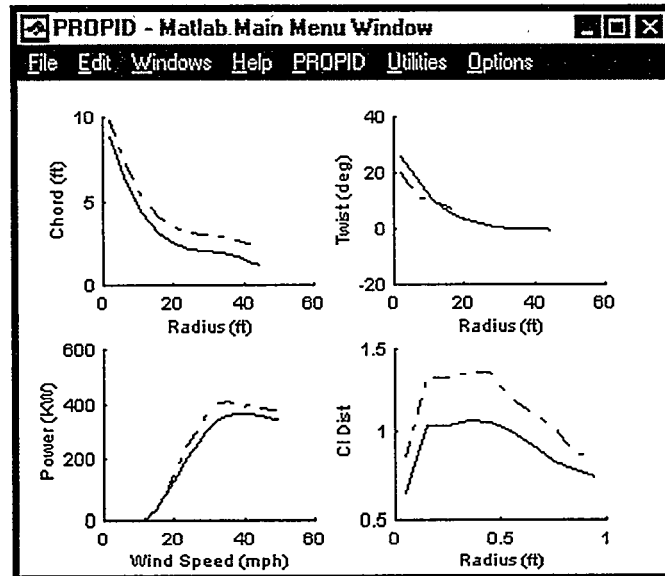
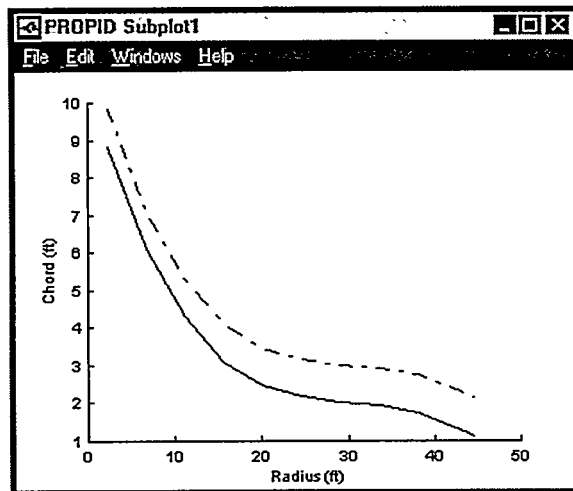
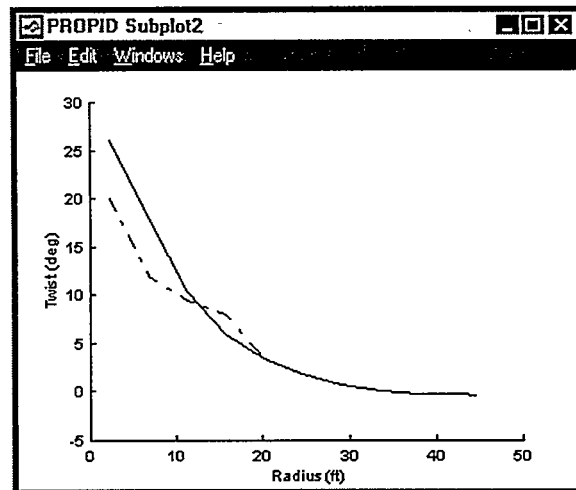


Figure 6. The Main Menu Window which contains the summary information, i.e. all plots in one view.



(a)
Figure 7. Individual subplot showing chord vs. radius distribution.



(b)
Individual subplot showing twist vs. radius distribution.

summary window, i.e. a window containing all the graphs in a single view. The values for the title, x-axis and y-axis labels are defined in the GRAPH.DAT file.

The PropID main menu and summary window is shown in Fig. 6. From this window all of the functionality of the application is controlled and executed. In this figure, it can be seen that multiple graphs are displayed, each containing results for the given number of cases and/or a reference plot (not included in Fig. 6). The line style and color can be defined as shown in the “Case Options” window (Fig. 4). Each of the graphs can also be plotted in an individual window, as seen in Fig. 7 (a) and (b). It is often easier to use a window containing a single plot. The window will typically display more detail and can be further enlarged (zoomed using mouse clicks) to reveal even higher resolution.

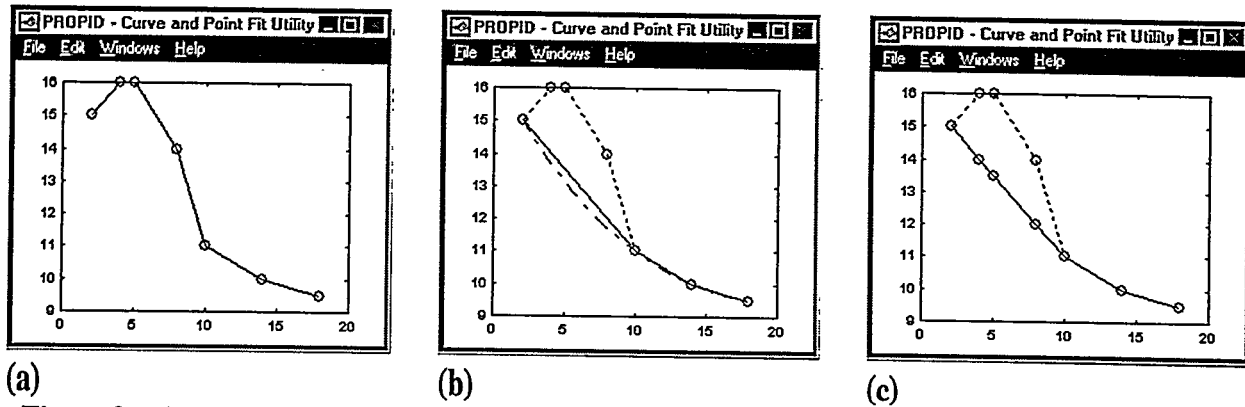


Figure 8. The series of figures shows the curve and point fit utility and demonstrates taking an original set of points, adding or removing points, and interpolating the current set of points with respect to the x values to get a new set of points.

PropID Curve and Point Fit Utility

The Curve Utility can be used for a variety of functions. This utility was designed to read in a set of ASCII data points and manipulate the points that can ultimately be used in PropID. Once the original points are read in, as seen in Fig. 8 (a), additional points can be added or removed from the curve to define a smoother or totally new curve. Figure 8 (b) demonstrates where some original points were removed and a spline was fit through the remaining points. In Fig. 8 (c) the newly defined curve was linearly interpolated using the original x-values as a basis to get the corresponding y-values.

In all of the above cases, it is possible to write out an ASCII file containing the corresponding values of the original curve, the splined data, the new curve, or the new curve after performing the linear interpolation. The resultant data can then be manipulated and used to create entries for the input file.

The Curve Utility feature is particularly useful when defining, for instance, a desired lift coefficient or axial induction factor distribution or more simply the chord and twist distributions for the “design by analysis” mode. For example, the utility could be used to first define the desired axial inflow curve at the defined stations along the rotor blade, then interpolate the curve to get the values at each of the blade stations, and then finally use these values in the input file.

Ongoing Development Activities

- Recently, the Corrigan & Schillings¹⁴ 3-D post stall model has been included in PropID to model the 3-D post stall delay effects. Evaluation of the model is currently underway,¹⁵ and it will soon become a standard feature of the code.
- Airfoil data entry into the PROP code has always been a cumbersome and time consuming task. As previously mentioned, PropID airfoil data is input simply by specifying the locations of the particular airfoils along the span together with the corresponding airfoil data file. A new add-on feature to PropID is the Matlab-based airfoil data viewer program that allows the user to easily inspect the airfoil data through a GUI. The interface also has an edit feature that allows the user to interactively modify the airfoil data in order to perform “what if scenarios” during a design session. For instance the polar data points are editable and make it possible to study the effects of increasing the lift coefficient, or

lift-to-drag ratio, and so on. Through this process, desirable airfoil attributes can be studied and used to aid in defining desirable airfoil characteristics for use in the airfoil design process.

- It should also be mentioned that efforts are underway to include WTPREP features into the PropID code. WTPREP¹⁶ is an airfoil data pre-processing program used to generate input data to PROP. It also generates airfoil data from ± 180 deg for use with HAWT dynamics codes that require airfoil data for all angles of attack. The new version of PropID will support all of the options in WTPREP.
- Due to the dynamic capability of the PropID FORTRAN code, it is not possible to implement each and every feature into the GUI interface and post-processor viewer. However, the GUI section is in ongoing development and new features are added continuously.
- The current Matlab GUI interface is designed using Matlab version 4.2.c. Unfortunately, this particular version is quite restrictive with respect to customizing the windows and GUI environment. A new version of Matlab, namely Matlab 5, has just recently been released in which most of these issues have been addressed and various additional features and functions have been added to increase the versatility and flexibility of the programming and user interface environment. Future plans involve porting the current code over to Matlab 5 to make use of its more advanced features.
- Creating the design and analysis input file for the FORTRAN code can be cumbersome and time consuming. It is virtually impossible to design an interactive input dialog that will account for every possible combination of all the input command/keyword sequences. However, it has been discussed to design a "batch input file assembler" that will aid the user in creating the input file. The assembler utility will have a set of all possible input keywords and entry formats. The user will assemble the input file by pointing and clicking on the various keywords. The possible values for the particular keyword will be displayed which the user can then edit and use to create an input line. The syntax of the input line will be checked and an entry for the input file will be assembled. When completed and checked for correctness, the entry will be appended to the end of the input file.
- The current PropID FORTRAN code does not have the ability to read columnar or tabulated ASCII data (such as those generated by the Curve Utility) for certain properties of the input file, such as axial inflow at each of the individual blade stations. This shortcoming will be addressed and such a feature will be implemented in the near future.

Conclusions

The newly added graphical display ability of PropID has increased the ease of use. Graphically displaying the results of each design and comparing the results on screen allows the user to quickly visualize the design and its performance. It is easy to compare the last couple of design cases and select the best design which can act as the foundation for successive designs, until a better design is created. Also, a reference case can be defined to aid in the evaluation of the design process.

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RECENT WIND RESOURCE CHARACTERIZATION ACTIVITIES AT NREL

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INTRODUCTION

The wind resource characterization team at the National Renewable Energy Laboratory (NREL) is working to improve the characterization of the wind resource in many key regions of the world. This work is especially important because the wind energy market is rapidly being transformed both in the United States and abroad. Wind characterization activities will help optimize wind measurement programs, enhance the development of wind energy, and lead to more opportunities in the electric wind energy industry.

Personnel who have had extensive experience in wind resource assessment lead the wind resource activity. The current expertise of the team includes meteorology, wind climatology, computer mapping using ARC/INFO Geographic Information Systems, and programming, and management of computer equipment used for wind resource assessment activities include development using FORTRAN, C, and PERL and UNIX-based operating systems on Sun Workstations.

Major wind resource assessment activities undertaken by NREL during the past year include:

1. Updates to the comprehensive meteorological and geographic data bases used in resource assessments in the United States and abroad
2. The development and validation of an automated wind resource mapping procedure
3. Support in producing wind forecasting tools useful to utilities involved in wind energy generation
4. Continued support for recently established wind measurement and assessment programs in the United States.

Expert private consultants and subcontractors ably support NREL's wind resource assessment tasks. Areas of support during the past year include wind monitoring station installation, training, and operation; analysis of wind and other meteorological data; wind resource assessment training and presentation; technical assistance in support of utility/industry requests; an inventory of recent U.S. wind measurement data; and surveys of numerical wind flow/prediction models and methods of re-constructing missing meteorological data.

METEOROLOGICAL AND GEOGRAPHIC DATA BASES

The comprehensive global data bases at NREL used for resource assessment activities for regions in the United States and abroad continue to be expanded and updated. These data bases contain the meteorological and geographical information that are the cornerstones for the development of an automated wind resource mapping tool used to produce sophisticated wind resource assessments.

NREL has data from a variety of meteorological and topographical data sets. The principal types of

meteorological data sets include surface data from first-order weather and aviation stations, upper-air data taken by weather balloons, and marine data measured by ships and satellites. A paper by Elliott and Schwartz (1996) describes these meteorological data sets in detail. Digital elevation data are the main type of geographic data sets used in wind resource assessment activities and are especially important in the production of advanced wind mapping tools. During the past year, NREL has obtained, from the United States Geological Survey, digital elevation data sets with 1 km resolution for much of the world. The resolution in these data sets is much finer than what was previously available to NREL and the use of finer resolution grids results in a more accurate wind resource map. The meteorological and geographic data sets have been used in the Mexico wind resource assessment project (Schwartz and Elliott, 1995), and for resource assessments in Indonesia, Chile, and a few other areas.

NREL's wind resource assessments helped optimize new measurement programs in areas shown by the wind maps to have good-to-excellent wind resource potential. Data collected from these new measurement stations are then integrated into the NREL data sets. Wind data from new monitoring stations in Mexico and Indonesia have been useful in refining the distribution of the wind resource in regions where wind energy projects are under consideration or development. Monthly wind power density values measured at several of the new monitoring stations on West Timor, Indonesia, (established and managed by Winrock International) are presented in Figure 1. In general, these data indicate the existence of good-to-excellent wind resources that were predicted by NREL's preliminary wind maps.

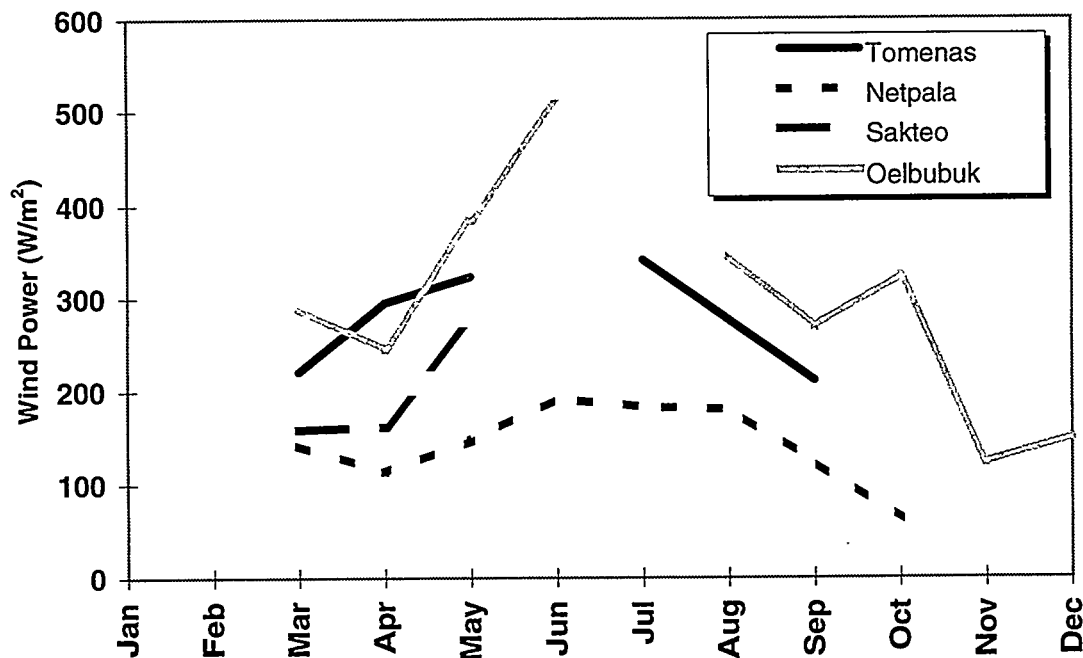


FIGURE 1: 1996 MONTHLY WIND POWER DENSITY VALUES OF 4 STATIONS IN WEST TIMOR, INDONESIA. THESE STATIONS WERE ESTABLISHED AS PART OF A DOE/USAID WIND RESOURCE ASSESSMENT PROJECT.

DEVELOPMENT AND VALIDATION OF WIND MAPPING TOOLS

The creation of automated progressive wind mapping tools is a key component in the production of sophisticated wind resource maps. The computer mapping system developed by NREL uses an analytic approach and portrays a regional distribution of the wind resource. The computerized mapping technique

greatly reduces the effort needed to create a wind map as compared to the old-style manual analysis, especially in areas of complex terrain. Computer mapping also analyzes the distribution of the wind resource in a consistent manner throughout the region of interest. The initial step in producing an automated wind resource map is to define the meteorological inputs used by the mapping system. These inputs are defined by the use of advanced analysis techniques based on information from the updated NREL data sets. A key task in deriving these inputs is the formation of a conceptual model that explains what causes the wind to blow in a certain region. The scale of the meteorological factors that cause the wind flow can vary from several hundred kilometers (storm-scale) to only a few kilometers when local circulations (e.g., sea-land breeze, mountain-valley circulation) predominate. A variety of meteorological data sources assimilated at NREL facilitates the process of conceptualizing wind patterns in most regions of the world. The diversity of the wind data sources also enables poor quality or suspect data from one data set to be checked and screened against data from other sources. The meteorological inputs derived from the advanced analysis techniques are then combined with digital elevation models and GIS software to produce wind maps showing the most favorable wind resource areas. Recent advances to the computer mapping tool developed by NREL (Elliott and Schwartz, 1996) include an algorithm to account for diminution of the wind resource caused by large-scale blocking (e.g., in the vicinity of an island with complex terrain) and a modification to the section that calculates the effect of terrain on the wind resource.

Validation tests are being designed and conducted on the wind resource mapping tool. These tests are using wind energy measurement data from the United States and other areas as a check that will help determine the effect of varying the input parameters and algorithms on map output and accuracy. Some of the factors being tested include upper-air data input, digital elevation grid data, and varying the algorithms that calculate the effect of the terrain on the distribution of the wind resource. The results of these tests will be used to modify existing software and to create, when necessary, new software to increase the accuracy of the mapping system.

WIND MAPPING PRODUCTS

An example of NREL's computer generated wind resource maps is shown in Figure 2, a resource map of the island of Sumba, located in southeastern Indonesia. This map was developed as part of a wind resource assessment project funded by DOE and USAID and administered by Winrock International. This island is characterized by moderately complex terrain and is in a band of moderate-to-strong easterly winds that predominate from April through October. The meteorological inputs for this map were aided by analysis of satellite derived ocean wind speeds, an upper-air climatic atlas data set, and weather balloon stations at Waingapu on Sumba and at Kupang on West Timor.

NREL has also produced computer wind resource maps for areas of Region 9 and Region 10 in south-central Chile in support of a DOE/EPA renewable energy development project. The process of producing computerized wind resource maps of Chile was more difficult than Sumba. The regions have more complex terrain (coastal range and Andes mountains) and a complex wind climatology. Several new algorithms were introduced into the mapping tool and modifications were made to existing ones to account for these factors. The Chile maps are being used to identify and target possible wind energy project sites for wind measurements.

WIND FORECASTING

Wind forecasting has been the subject of interest in the wind energy community for a significant number of years. Due to the recent availability of new data sets, advances in computing power, and advances in numerical weather prediction models, the development of automated wind forecasting tools of value to wind energy operators is now more probable. The initial wind forecasting tools developed as a result of this project will most likely be derived from wind speed forecasts since speed forecasts are produced by computer weather

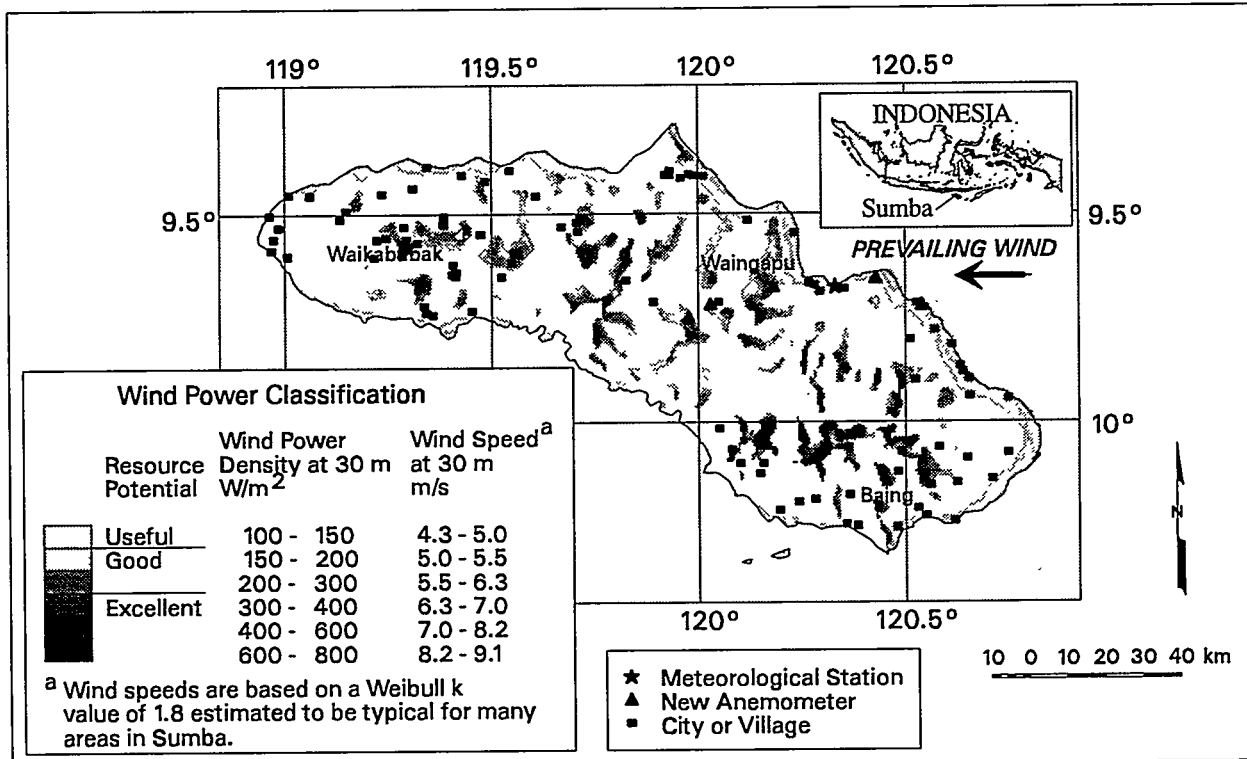


FIGURE 2: COMPUTERIZED WIND RESOURCE MAP OF SUMBA, INDONESIA

prediction models. This enables wind speed forecasts to be directly evaluated as to their suitability to wind energy applications. Research on wind power generation forecasts will follow evaluations of wind speed forecasts. Recent activities undertaken by NREL for the wind forecasting task include evaluating the accuracy of the wind forecasts produced by a routinely run numerical weather prediction model and beginning a dialogue with utilities to get their views on the most useful types of wind forecasting tools.

The Rapid Update Cycle (RUC) is an advanced numerical weather prediction model used to generate weather forecasts for the United States. The model was developed at the National Oceanic and Atmospheric Administration's Forecast Systems Laboratory (FSL) in Boulder, Colorado. This model was chosen by NREL to be evaluated for wind forecasting accuracy in part because its predictions of wind speed and direction have higher temporal and spacial resolution compared to other numerical weather prediction models. NREL and FSL are partners in the evaluation activity. FSL is currently archiving model predictions and writing software in support of this activity.

NREL, with help from its support subcontractor for wind resource assessment (AWS Scientific, Inc.), is engaged in a fact-finding initiative, targeted at the operators of utility systems, on the potential use of wind forecasts by utilities for predicting wind plant generation output. Interviews are being conducted with operators and other utility staff from several Utility Wind Interest Group (UWIG) member utilities to obtain their feedback about the use and types of wind forecasts that would fit their needs plus some background information about the utility's operating system. The findings from this series of interviews will serve as a basis of a possible wind forecasting development program tailored to utility interests.

UNITED STATES MEASUREMENT AND ASSESSMENT PROGRAMS

NREL continues to help oversee the three recently initiated DOE cost-shared programs that include wind measurement and resource assessment activities in the United States: 1) the Utility Wind Resource Assessment Program (U*WRAP), 2) the Sustainable Technology Energy Partnerships (STEP), and 3) the Cooperative Networks for Renewable Resource Measurements (CONFRRM). The goal of these programs is to accelerate multiregional U.S. market penetration of wind systems and to move the United States towards leading the world in the development and use of advanced wind turbine technology. The programs are designed to form partnerships with diverse types of organizations including state and tribal energy offices, private and public utilities, universities, research institutions, the financial community, and private consulting firms that wish to help accelerate the commercial development of wind energy.

U*WRAP, administered by UWIG, is a program designed to technically and financially support private and public utilities conducting wind resource assessments. This program will increase the quantity of wind data available to utilities and enlarge the qualified workforce that can conduct a skilled resource assessment program. The results from the U*WRAP program will give utilities the means to assess their wind resources and wind electric potential, identify candidate development areas, target the most compatible wind turbine designs, and assess the economics of wind-based generation. Six utilities are participating in U*WRAP; a total of 34 wind measurement stations have been established. The time frame for the U*WRAP measurements is two years, so most of the monitoring will be completed in 1997 and 1998. The data collected by the utilities under this program will be proprietary for up to 5 years after the start of the measurements because the utilities are cost-sharing one-half of the cost of U*WRAP. After 5 years the data will be made available to the public.

STEP seeks to meet the needs of states, industry, and localities in accelerating the commercialization of renewable energy technologies. One of the areas of interest of the STEP program is wind resource assessment. The STEP program actively supports the establishment of new measurement stations in areas being considered for wind power generation and analysis of existing wind data using GIS techniques leading to detailed areal resource characterization. The states of Colorado, Iowa, Minnesota, Nebraska, New Mexico, and Wisconsin are participating in this area of STEP.

CONFRRM is designed to improve the assessment of solar and wind energy resources in the United States. This program supports the establishment of long-term wind measurement benchmark stations at locations with high wind energy potential. The benchmark stations are located at sites that are representative of areas where wind technology applications appear feasible. There are no restrictions on the type of organizations that are responsible for the operation and maintenance of the benchmark stations. The data collected from the stations will be in the public domain and will be made available through NREL's Renewable Resource Data Center. Twelve wind measurement stations are currently in operation.

Figure 3 shows the distribution of the twelve states that presently have projects under these three programs. The states are concentrated in the Great Plains and Rocky Mountains, the regions with the highest overall wind resource potential in the United States, but other sections of the country, such as the Northeast and the Great Lakes, with a promising wind resource are also represented. Projects in additional states are likely to be funded in the near future. The three cost-shared programs should significantly increase detailed wind resource assessments and accelerate the commercialization of wind energy in the United States.

NREL provides technical assistance to wind resource assessment programs run by non-federal agencies such as state and tribal offices and utilities. The assistance, based on past NREL experience, can include reviewing the station siting approach and procedures, offering historical perspectives on wind resource assessment activity in a region, and offering advice on enhancing wind measurement programs. An example of this type of assistance was the help NREL provided through its support subcontractor to the Tennessee Valley Authority

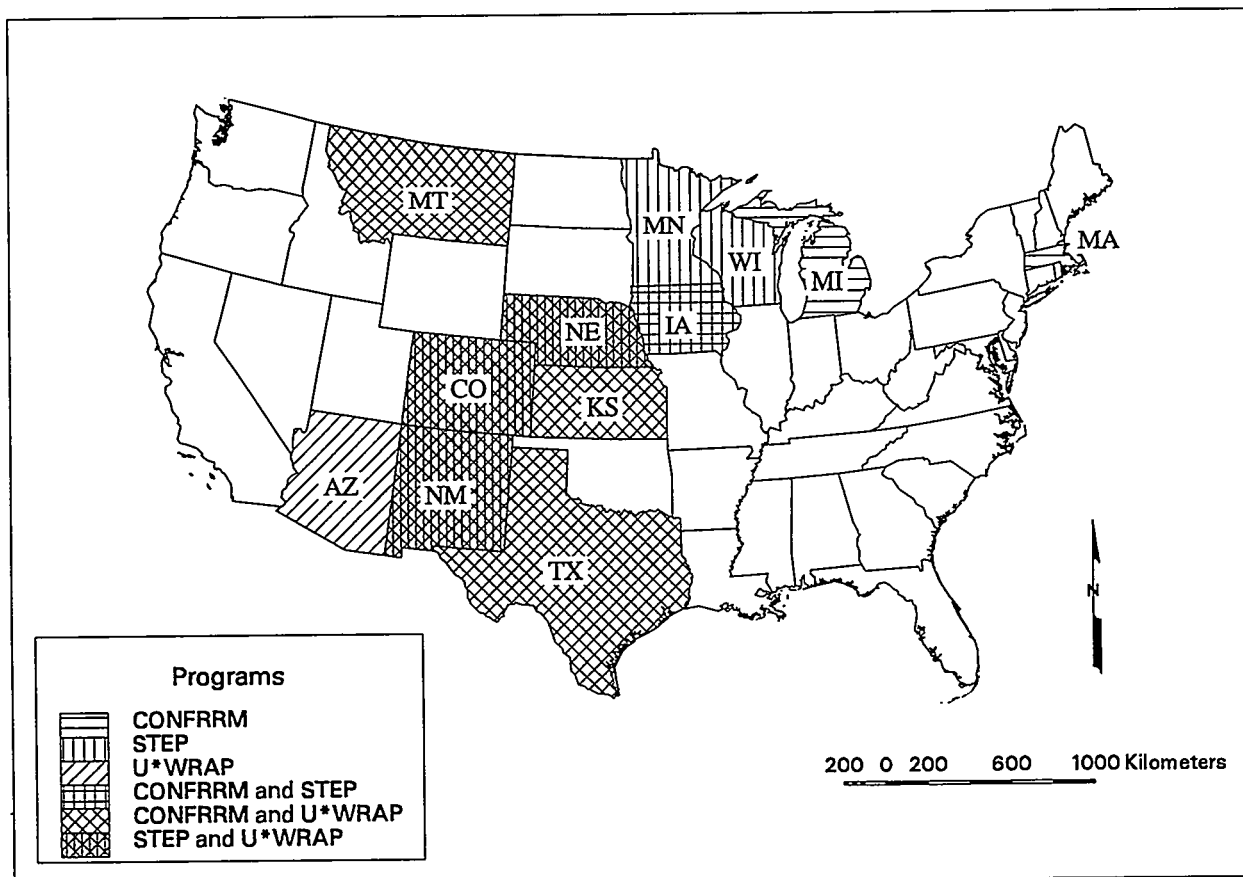


FIGURE 3: STATES HAVING PROJECTS UNDER DOE WIND MEASUREMENT PROGRAMS

in reviewing its methodology for choosing a wind monitoring site and aiding in the installation of that site in southern Kentucky. NREL has also recently published the *Wind Resource Assessment Handbook (1997)*. This handbook is suitable for any organization or individual desiring to conduct a structured wind measurement program. The information contained in the handbook was the basis for the NREL sponsored short-course "Conducting a Wind Resource Measurement Program", presented at the Windpower '96 and Windpower '97 conferences.

CONCLUSION

The wind resource assessment program at NREL is involved in a wide variety of activities with the purpose of accelerating the deployment of wind energy. Chief among the activities are developing and validating an automated wind mapping tool and using this tool to produce advanced and sophisticated wind resource maps. Other significant NREL activities include wind forecasting research, identifying and updating comprehensive databases used for wind resource assessment, and providing support to utilities and the wind energy industry in their resource assessment programs.

NREL will continue to expand the capabilities of the automated wind mapping technique in order to produce reliable wind maps of regions with quite complex terrain and/or wind flow. NREL also anticipates engaging in cooperative activities with utilities, industry, state agencies, universities, and private organizations to improve the wind characterization in the United States. The activities of the NREL wind resource assessment group will continue to be a key component in efforts to provide market opportunities for the domestic wind energy industry.

ACKNOWLEDGMENTS

We would like to thank George Scott and Ray George for their outstanding contributions to software and data processing development and Steve Haymes for his tireless work on creating the GIS mapping system. This paper was written at the National Renewable Energy Laboratory in support of the U.S. Department of Energy under contract number DE-AC36-83CH10093.

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WIND/SOLAR RESOURCE IN TEXAS

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ABSTRACT

Data are being collected at 17 sites to delineate a baseline for the wind and solar resource across Texas. Wind data are being collected at 10, 25, and 40 m (in some cases at 50 m) to determine wind shear and power at hub heights of large turbines. Many of the sites are located in areas of predicted terrain enhancement. The typical day in a month for power and wind turbine output was calculated for selected sites and combination of sites; distributed systems. Major result to date is that there is the possibility of load matching in South Texas during the summer months, even though the average values by month indicate a low wind potential.

INTRODUCTION

Texas has an enormous wind and solar energy potential due to large land areas of above average wind power and solar insolation [1]. The Alternative Energy Institute (AEI) estimated the capturable wind energy potential at 130,000 MW on accessible lands from wind class 3 and above. The solar potential is estimated at 250 Quads/yr. For both solar and wind, the primary resource areas are quite distance from the major electrical load centers. Even though the Texas is a major producer of oil, gas and coal, in the mid nineties the State became a net energy importer. Because of projected population growth of 2.7% per year and the following inherent growth in energy, even with conservation and efficiency, the State must becoming a leader in the use and technology of renewable energy.

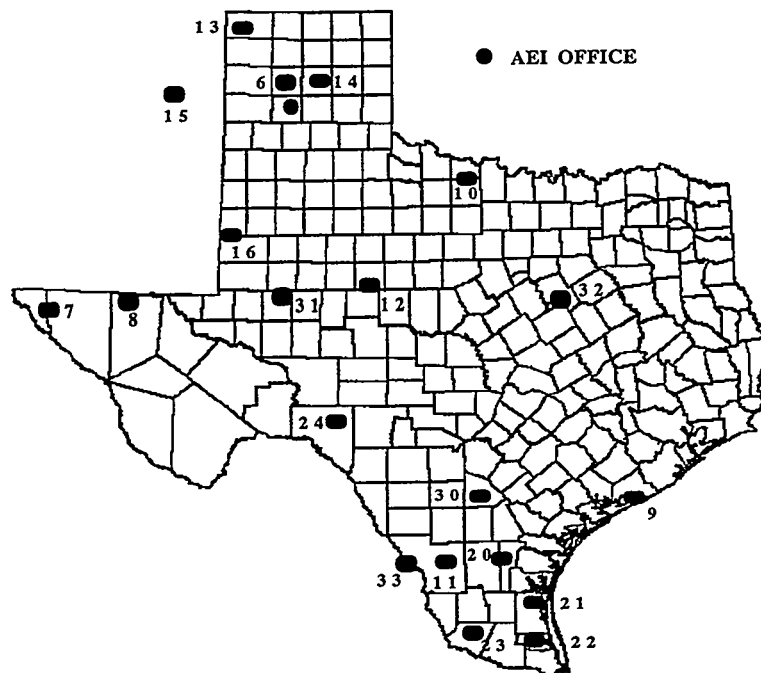
The General Land Office, along with Lower Colorado River Authority, was the leader in developing a wind plant (35 MW) in the Delaware Mountains, an excellent wind site [2]. Central and South West Systems has a program of measuring wind and solar at over 20 sites across their territory [3]. They have also installed a 6 MW wind plant and a PV demonstration project near Fort Davis.

As at other locations in the Great Plains, there is more wind energy at 50 m in the summer than predicted from the data at 10 m due to wind shear. The wind map of NREL was modified using Geographic Information Systems and terrain enhancement [1,4].

MEASUREMENT STATIONS

AEI is collecting data from 16 stations across Texas and 1 station in New Mexico (Fig. 1). Quite a few of these on located in areas of predicted terrain enhancement. Stations 13-15 (50 m guyed towers) were installed by SeaWest and purchased by AEI in 1996. At most stations existing towers were used (primarily Texas Department of Transportation) and two are NRG tall towers. An agreement had to be signed that AEI would assume liability for installation and operation of the data station,

Data collected are windspeed (Maximum cup anemometers), wind direction (Maximum), temperature, and solar insolation (Table 1). At some sites on existing towers, an upper level of windspeed was added (generally 50 m). Two windspeed sensors would be placed at the upper level, with only 1 sensor at 10 and 25 m. Data are sampled at 1 Hz and average over 15 minutes using NRG 9300 cell loggers. Data are transferred weekly to the base station at AEI.



#	Name	Lat (N)		Long (W)		Elevation
		Deg	Min	Deg	Min	m
CONFIRM						
7	Hueco Mountains, 40 m	31	48	106	00	1534
8	Guadalupe Pass, 40 m	31	51	104	49	1524
9	Matagorda	28	42	95	56	3
10	Blue Grove	33	48	98	11	305
11	Mirando City	27	24	98	58	269
12	Maryneal	32	13	100	27	762
24	Carta Valley (Del Rio)	29	44	100	4	610
UWRAP						
6	Southwestern Public, 40m tower	35		101		1130
13	Dalhart	36		102		1287
14	White Deer	35		101		1097
15	Quay, NM	34		103		1520
16	Denver City	32		102		1076
SOUTH TEXAS PROJECT						
20	Alice	27	50	98	05	71
21	La Paloma (Sarita)	27	14	97	56	11
22	Raymondville	26	30	97	47	15
23	Rio Grande City	26	32	98	42	147

FIGURE 1. LOCATION OF DATA STATIONS.

TABLE 1. SENSORS AT STATIONS.

Level, m	Windspeed	Direction	Other
3			Temperature, Li-Cor (horizontal, vertical)
10	2	1	
25	2	1	
40	2	1	

One of the more difficult tasks is determining if suitable cellular phone communications exist in the area and then recording the cellular phone into the local cellular system. NRG has standardized the basic equipment so each site is identical in hardware and the only change is entering the correct Electronic Serial Number (ESN) in the local cell service provider and correctly entering the new area code and telephone number into the data logger. A problem arises if there is a failure of the logger due to lightning or power loss and there is a need to replace the logger. Persuading cellular companies to change the ESN and leave all other details the same often takes several phone calls/faxes to establish that there is a need and desire to do this in the field. Another problem is if the directional antenna is displaced or there is a problem with the service provider, then the call can be routed through a cellular service and a large roaming charge results. We have had calls routed through Mexico.

DATA COLLECTION AND ANALYSIS

A PC receives the incoming data using the program Base, which is part of the NRG package. Calls generally take place between 10 PM and 6 AM to take advantage of lower phone rates. The serial port can be used to download data from data cards using a handheld Termreader. Data cards are the backup when there is a failure in the cellular transfer. At the averaging time rate of 15 min, a data card can store 1.5 months for the 12 sensors. The BASE program consists of four parts: scheduled maintenance, time keeping synchronization, site information/record keeping of calls, and collecting data.

The raw data are archived to sub directories and stored on hard drive and floppy disks. Data are transferred to another PC for analysis using the program Microsite. Microsite contains all the modules for importing, examination/verification of data streams, printout of preliminary reports and generation of summary pages showing the average, standard deviation, minimum and maximum for each sensor by any time period up to a month.

Microsite includes programs for calculating and graphing diurnal and monthly patterns (Fig. 2). During the wind storm of 1/17/96 that damaged a number of wind turbines at the Texas Wind Power Plant, at Site 8 the maximum windspeed was 57 m/s and the high 15 minute average was 41 m/s. Also a program was written to analyze the data by calculating a typical day for month by site and for combination of sites, a distributed system.

RESULTS

Annual averages (Table 2) show the same general pattern as the NREL wind map. The Delaware Mountains are an excellent site, with average power around 700 W/m² at 10 to 40 m. There is essentially no wind shear, therefore tall towers for wind turbines are not needed. Also the winds are primarily from the west-east, so a wind wall could be installed. The winds along the Gulf Coast are low even though Site 9 is right along the coast, while Sites 21 and 22 are around 20 miles from the coast. Hueco Mts (Site 7) is quite low even though it was formerly classified as higher due to terrain. Spring has the higher winds with summer being the low wind months (Fig. 3).

Site 15 is on a mesa and Sites 10, 11, 12, 14 and 24 are on elevated terrain. In general there is a speed and power increase at 40 m due to terrain. Note that the data at Site 15 are skewed toward higher values since July and August are missing. Another very interesting result is that Site 11 shows an increase in power from 40m to 50m (Fig. 4) compared to the rise from 10m to 40m.

Even though the average power by month is low for South Texas, the typical day for a month (average of 15 min periods) was calculated for sites 22, 23, 11, and 24; an arc along the Rio Grande River. The power increases in late afternoon with the sites further from the coast peaking at a later time (Fig. 5). For the High Plains, there is a larger shear at night in May-July due to thunderstorms building up in the late afternoon (Fig. 6). The solar power for a typical day is much higher. Figure 7 shows the wind and solar power for a distributed system in service territory of Southwestern Public Service. However when

TABLE 2. ANNUAL AVERAGE WINDSPEED AND POWER FOR 1995 AND 1996.

1995		Height 10 m		Height 40 m		Height 50 m		Comments
		Speed	Power	Speed	Power	Speed	Power	
#	Name	m/s	W/m ²	m/s	W/m ²	m/s	W/m ²	
6	SPS	6.0	215	6.7	272			
7	Hueco Mts	4.0	78	4.7	127			
8	Guadalupe Pass	8.4	654	8.5	651			
9	Matagorda	3.8	62	5.5	149	5.5	148	Data Mar-Dec
10	Blue Grove	4.3	89	5.7	164	6.2	213	Data Mar-Dec
11	Mirando City	4.6	103	5.8	170	6.7	298	Data Feb-Dec
12	Maryneal	4.6	99	6.1	193	6.5	231	Upper level 45 m
24	Carta Valley	4.0	57	5.6	143			Data Aug-Dec
20	Alice	3.1	43	4.2	78			Data Aug-Dec
21	La Paloma	2.7	34	4.3	81			Data Aug-Dec
22	Raymondville	3.5	57	4.5	81			Data Aug-Dec
23	Rio Grande City	3.2	45	4.8	105			Data Aug-Dec

1996		Height 10 m		Height 40 m		Height 50 m		Comments
		Speed	Power	Speed	Power	Speed	Power	
#	Name	m/s	W/m ²	m/s	W/m ²	m/s	W/m ²	
6	SPS	6.4	248	7.0	309			
13	Dalhart	5.3	143	6.7	230	7.0	292	Data May-Dec
14	White Deer	5.8	165	7.7	372	7.8	388	Data Mar-Dec
15	Quay, NM	5.6	198	6.2	321	5.9	441	Data Mar-Dec: 50 m, No Jul-Aug
16	Denver City	3.7	54	5.9	174	6.0	185	Data Apr-Dec
7	Hueco Mts	3.9	69	4.6	114			
8	Guadalupe Pass	8.9	789	8.6	710			
9	Matagorda	4.1	68	5.8	177	5.8	180	
10	Blue Grove	4.8	128	6.1	214	6.7	274	
11	Mirando City	5.2	133	6.3	211	7.5	379	
12	Maryneal	4.7	106	6.3	203	6.7	238	Upper level 45 m
24	Carta Valley	4.8	90	6.5	216			
20	Alice	4.2	79	5.3	140			
21	La Paloma	3.8	67	5.5	160			
22	Raymondville	4.5	106	5.5	157			
23	Rio Grande City	4.6	99	6.3	212			

averaged over 24 hours, the solar power will be much lower. The advantage of solar is that there is a much better load matching during the summer months.

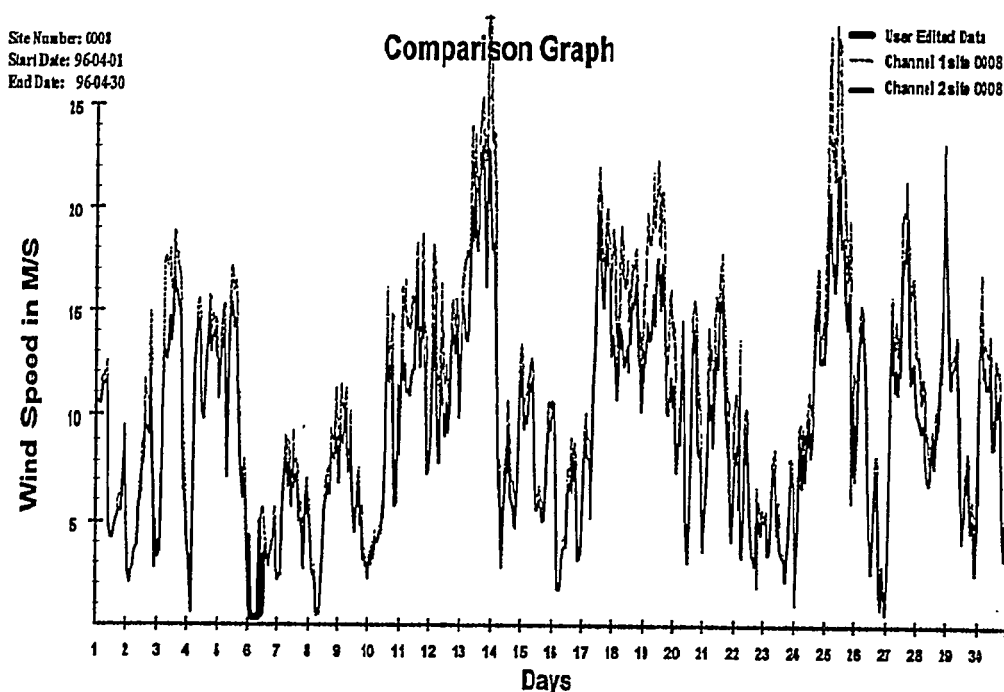


FIGURE 2. HOURLY WINDSPEED, M/S, AT 10 M HEIGHT FOR GUADELUPE PASS, APRIL 96.

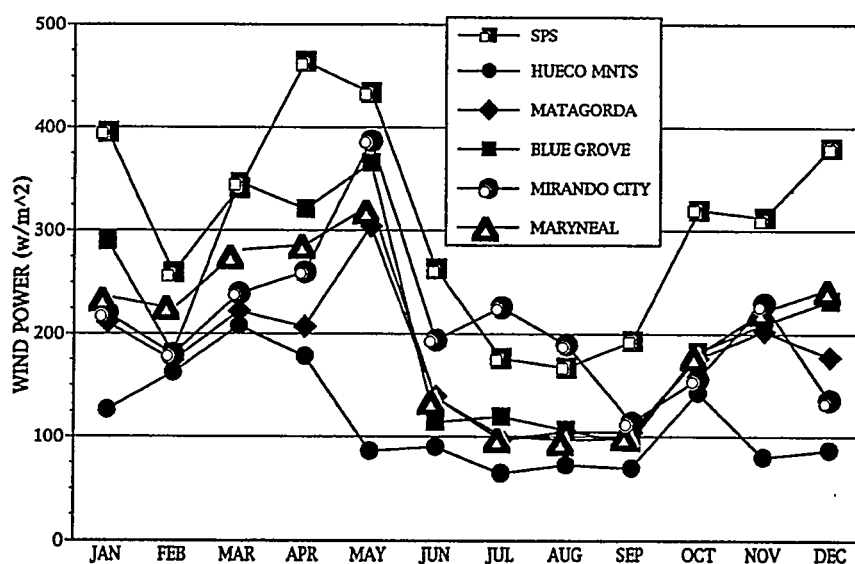


FIGURE 3. WIND POWER (40 M) FOR SELECTED STATIONS ACROSS THE STATE, 1996

WIND TURBINE POWER

The power curve for a Zond Z40 was used to calculate the power for each 15 minute period. The standard deviation was around 75 kW. As expected the power produce by a wind turbine for a typical day follows the power for the typical day (compare Fig. 8 to Fig. 5). The solid line in Figure 8 is the average of the

curves, the output from a distributed system. The typical day is a simple method to calculate the capacity factor by month or by selected time periods in the typical day (Table 3)

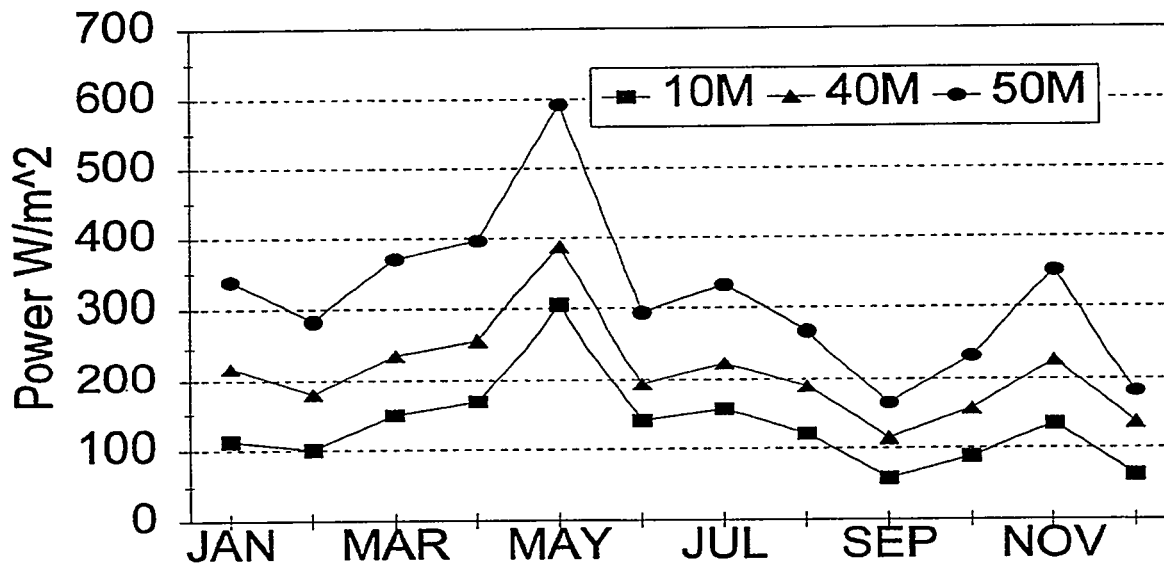


FIGURE 4. MONTHLY POWER FOR MIRANDO CITY, 1996.

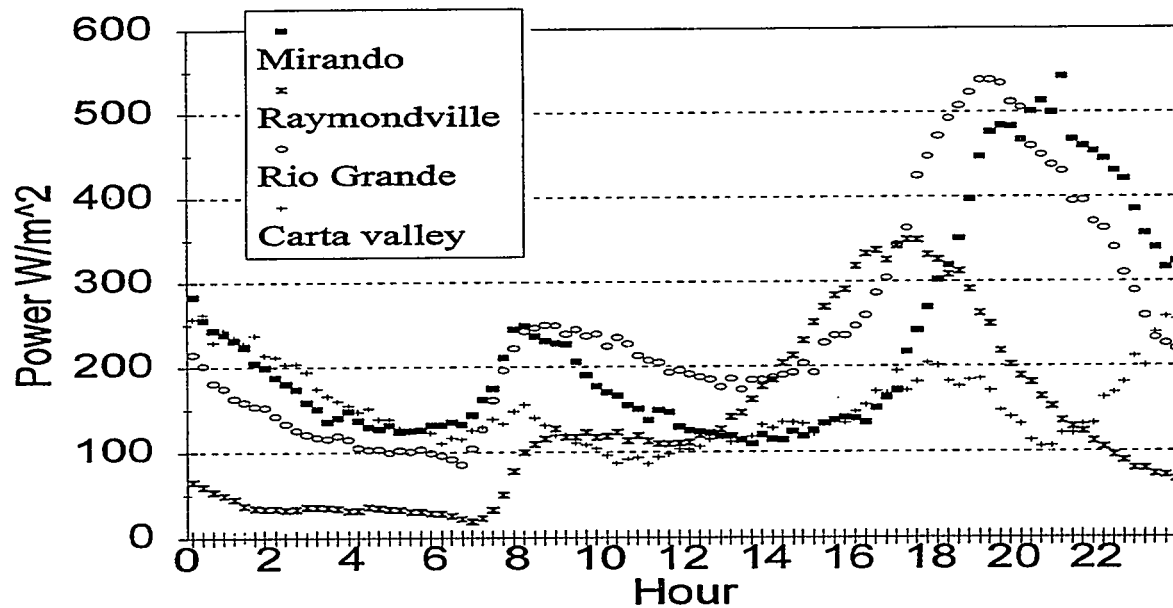


FIGURE 5. WIND POWER FOR TYPICAL DAY, JULY 96.

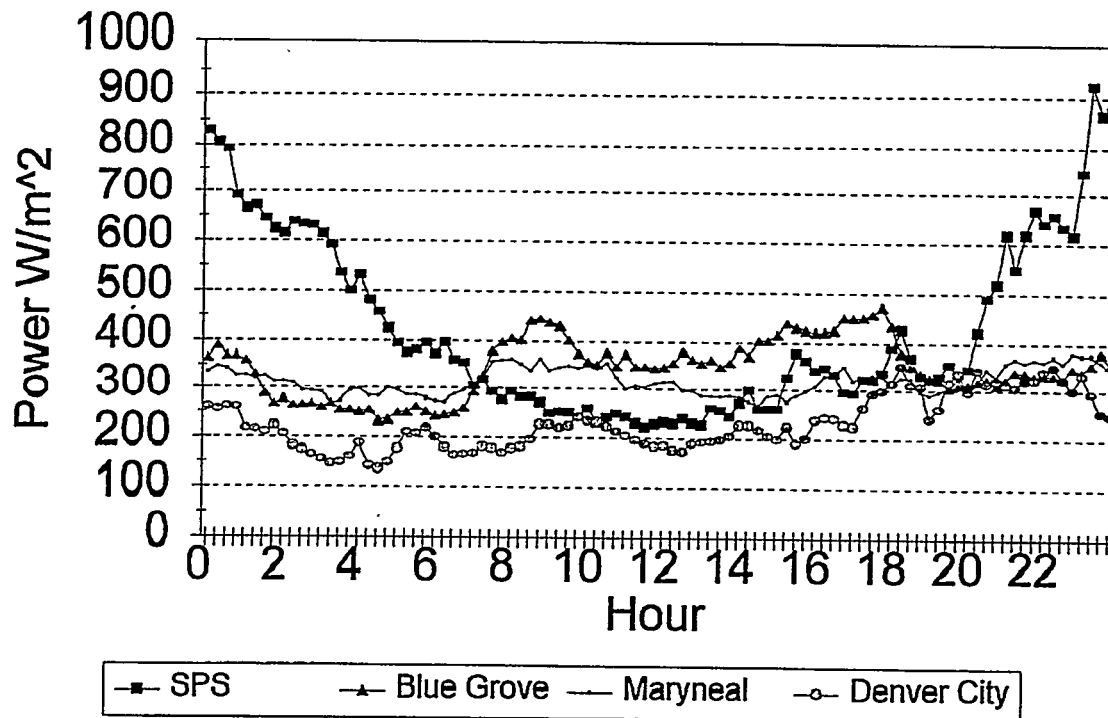


FIGURE 6. WIND POWER FOR TYPICAL DAY FOR HIGH PLAINS, MAY 96.

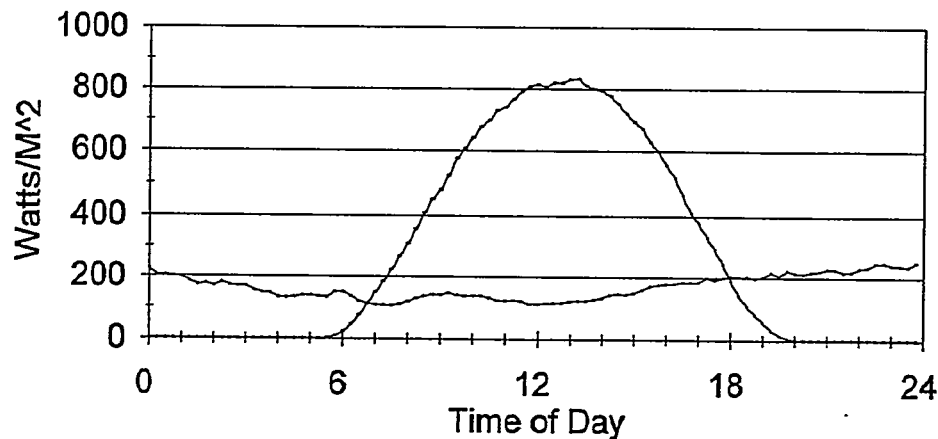


FIGURE 7. TYPICAL DAY FOR WIND AND SOLAR POWER FOR SITES 6, 13-16, JULY 96.

FUTURE WORK

Wind and solar data for a typical day in a month will be calculated for each site and for distributed systems. Load data for utilities in four regions (SPS, High Plains, South Texas, and the State) will be compared to the power output for a typical day. Sites 7, 21, and 20 will be removed, a new site will be installed within 2 miles of the coast between Corpus Christi and Brownsville. Data will be collected for another two years at the remaining sites to determine a baseline data set for the State.

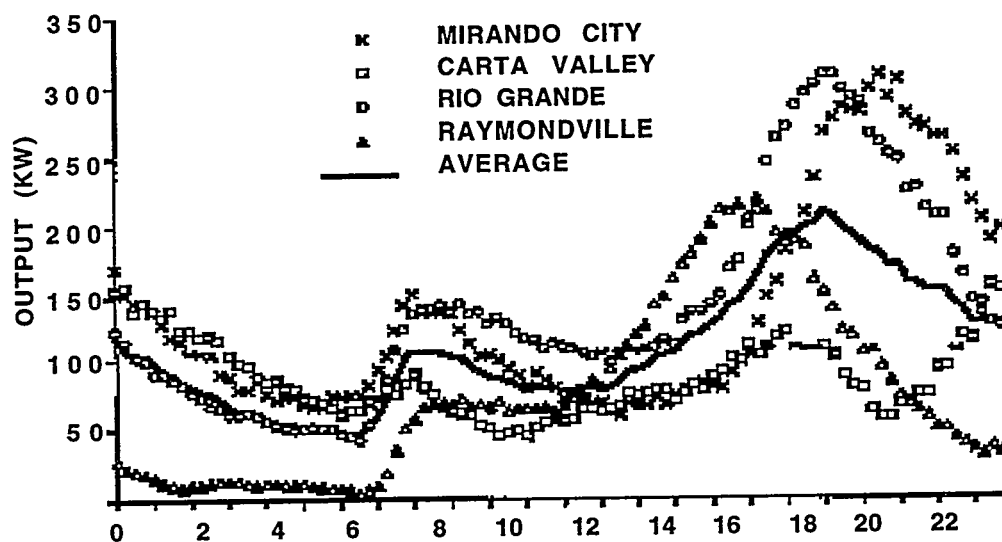


FIGURE 8. POWER OUTPUT FROM Z40 FOR TYPICAL DAY, JULY 96.

Table 3. AVERAGE POWER AND CAPACITY FACTORS FOR Z40 WIND TURBINE, JULY 96.

Site Name	Month		14:00-24:00	
	Power, kW	CF, %	Power, kW	CF, %
22 Raymondville	77	15	129	26
23 Rio Grande City	140	28	204	41
11 Miranda City	136	27	188	38
24 Carta Valley	88	18	95	19

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ACKNOWLEDGEMENTS

Initial support came from the State Energy Conservation Office (4014 and 95-139R) and AEI, and then funding to help continue the projects came from Southwestern Public Service and NREL (Utility Wind Resource Assessment Program, 5023-01), NREL (CONFRRM, RCF-5-15026) and Texas Energy Coordination Council (UTA 96-0219).

**Predicting Wind Shear Effects:
A Study of Minnesota Wind Data Collected
at Heights up to 70 Meters**

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ABSTRACT

The Minnesota Department of Public Service (DPS) collects wind data at carefully selected sites around the state and analyzes the data to determine Minnesota's wind power potential. DPS recently installed advanced new monitoring equipment at these sites and began to collect wind data at 30, 50, and 70 meters above ground level, with two anemometers at each level. Previously, the Department had not collected data at heights above ground level higher than 30 meters. DPS also, with the U.S. Department of Energy (DOE), installed four sophisticated monitoring sites as part of a Tall Tower Wind Shear Study that is assessing the effects of wind shear on wind power potential. At these sites, wind data are being collected at the 10, 30, 40, 50, 60, and 70 meter heights. This paper presents the preliminary results of the analysis of wind data from all sites. These preliminary results indicate that the traditional $1/7$ power law does not effectively predict wind shear in Minnesota, and the result is an underestimation of Minnesota's wind power potential at higher heights. Using a power factor of $1/5$ or $1/4$ may be more accurate and provide sound justification for installing wind turbines on taller towers in Minnesota.

INTRODUCTION

Minnesota has an extensive wind resource. Estimates are that this resource, if fully developed, could produce 14 percent of the total electrical needs of the continental United States (Hock, Thresher, and William, 1992). Because of the many benefits that come from renewable-based electric generation, there is considerable support in the state for developing Minnesota's wind resource. Northern States Power, a major investor owned utility in Minnesota, is committed to having 247.65 Megawatts of wind farm capacity operating in Minnesota by 1998.

This paper presents an analysis of the wind resource data collected through the DPS Wind Resource Assessment Program (WRAP) and the DPS/DOE Tall Tower Wind Shear Study. The analysis concentrates on the wind shear found at sites across Minnesota. The results are in some cases based on less than one year of data, and therefore should be considered preliminary.

WRAP SITES

In 1995 DPS upgraded the equipment, equipment configuration, and siting of the WRAP sites. All of the WRAP sites discussed in this paper are equipped with cellular data loggers that call into the base station computer every other day. These sites use existing communication towers and have monitoring levels at 30, 50, and 70 meters above ground level. Two anemometers are mounted at each level, one on each side of the tower. This configuration reduces the wind shadow effect the tower would have on the data if only one anemometer were used at each level. This configuration also provides a degree of

redundancy at each level so that the failure of one sensor does not eliminate the data collection at that level. Two sensors at each level also provide the opportunity to do sensor-to-sensor calibration and help diagnose potential problems with sensors. Each tower is also equipped with wind vanes at the 30 and 70 meter levels. In addition to the internal logger temperature, some of the sites are equipped with external temperature probes mounted at approximately 4 meters above ground level.

All of the newly equipped WRAP sites were carefully chosen to represent the surrounding countryside. One of the siting criteria was to not allow any significant nearby obstructions. Of the 21 older WRAP sites operating when the new equipment was installed, only three were considered to meet the new siting criteria and were re-equipped. The newly equipped WRAP sites are distributed across the southern and western parts of Minnesota (see Figure 1). In addition to the 12 WRAP sites considered in this paper, two new 70-meter sites near the towns of Rochester and Elk River are shown on Figure 1, but are too new for analysis in this paper.

TALL TOWER WIND SHEAR SITES

In 1996 DPS installed four very advanced monitoring sites as part of the DPS/DOE Tall Tower Wind Shear Study. These sites use existing communication towers and have monitoring levels at 10, 30, 40, 50, 60, and 70 meters above ground. As with the WRAP sites, each monitoring level has two anemometers, one mounted on each side of the tower. Each tower is also equipped with wind vanes at the 10, 30, 60, and 70 meter levels.

The Tall Tower sites were carefully chosen to represent the surrounding countryside, and none of the sites have nearby significant obstructions. The Tall Tower sites are distributed across the state, with one site near the town of Clarks Grove in south central Minnesota at an elevation of 402 meters (1320 feet). Two Tall Tower sites are in southwestern Minnesota: one is near the town of Chandler on the Buffalo Ridge at an elevation of 556 meters (1825 feet), and the other site is near the town of Marshall. This site is north and east of the Buffalo Ridge at an elevation of 451 meters (1480 feet). The Buffalo Ridge area of Minnesota is currently the site of significant wind farm development. The fourth site is on the central western edge of Minnesota in the Red River Valley near the town of Breckenridge at an elevation of 295 meters (968 feet). See Figure 1 for locations of the Tall Tower Sites.

CUMULATIVE AVERAGE VERTICAL WIND SHEAR (WRAP SITES)

The configuration of the WRAP sites allows for calculating vertical wind shear for the 30 to 50 meter and the 50 to 70 meter height differences or layers. An automated calculation process was established to determine the vertical shear values for these two layers for all sites. The calculation process excluded shear values for wind speeds less than 2.2 meters-per-second, to reduce the effect on the average from the greatly varying shear values produced by very low wind speeds. The data considered in the averaging process were filtered using an existing data validation routine. This data validation routine marked data as invalid due to equipment failure or icing. For most of the WRAP sites, approximately 23 months of data were considered in the average calculations. The average calculation first determined the average for each month and then averaged the twelve months, to reduce the effect of having multiple months of data for some months and not others.

The cumulative average vertical wind shear values for the 12 WRAP sites are shown in Figure 2. The traditional 1/7 power law for determining wind shear uses a wind shear alpha factor of 0.14. The values shown on this graph range in value from 0.185 for the Currie site at the 30-50 meter level to 0.378 for the Brownnton site at the same level. This indicates that using alpha factors in the range of 0.14 in the wind

Minnesota 70 Meter Wind Resource Assessment Sites

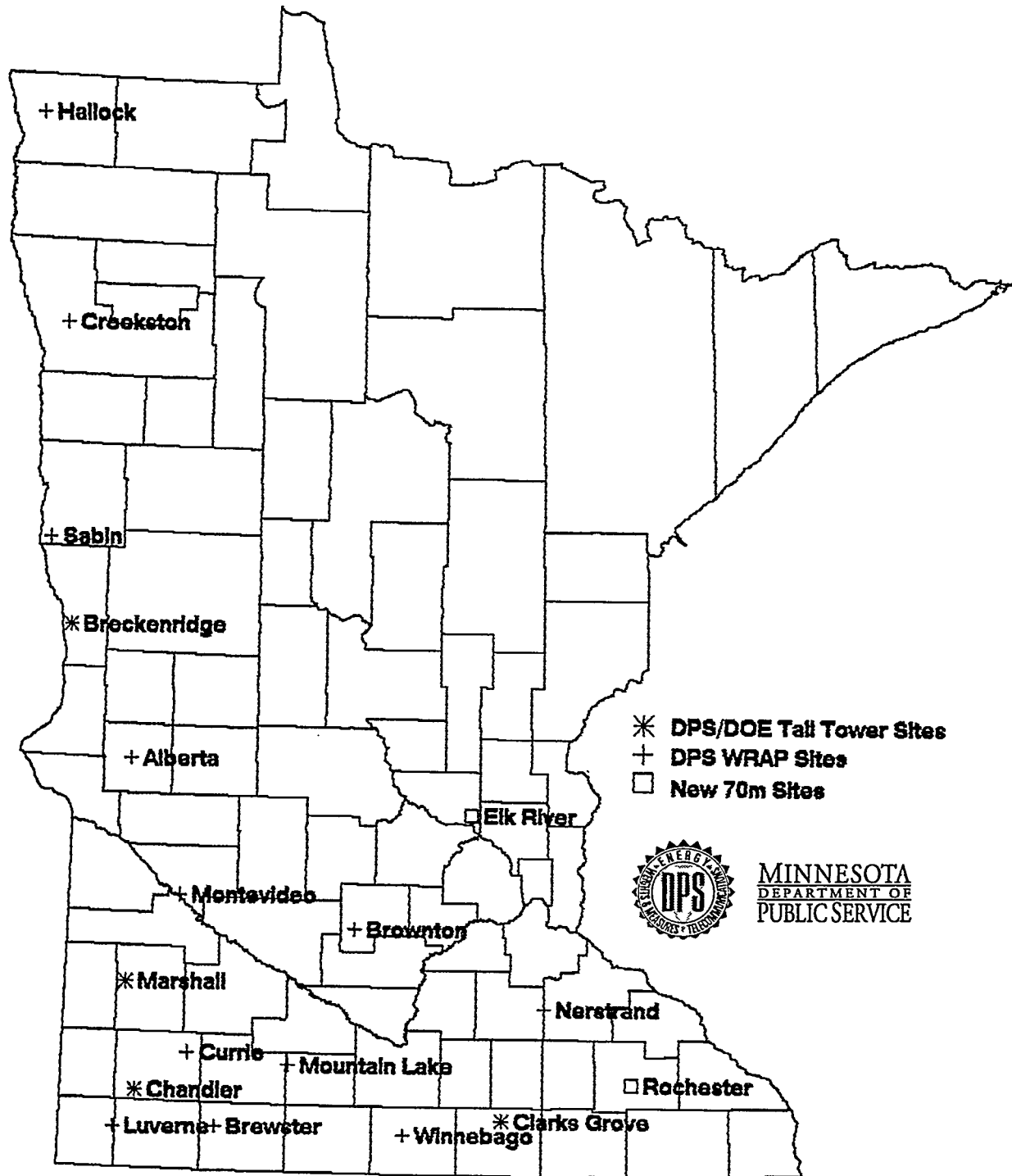


Figure 1

shear power equation will tend to underestimate the effects of wind shear when estimating wind power in Minnesota. Without site specific information on wind shear, a conservative average shear value for use in the wind shear power equation may be more in the range of 0.18. When estimating the effects of wind shear near these monitoring sites, typical values for the wind shear alpha will range from 0.20 to 0.25.

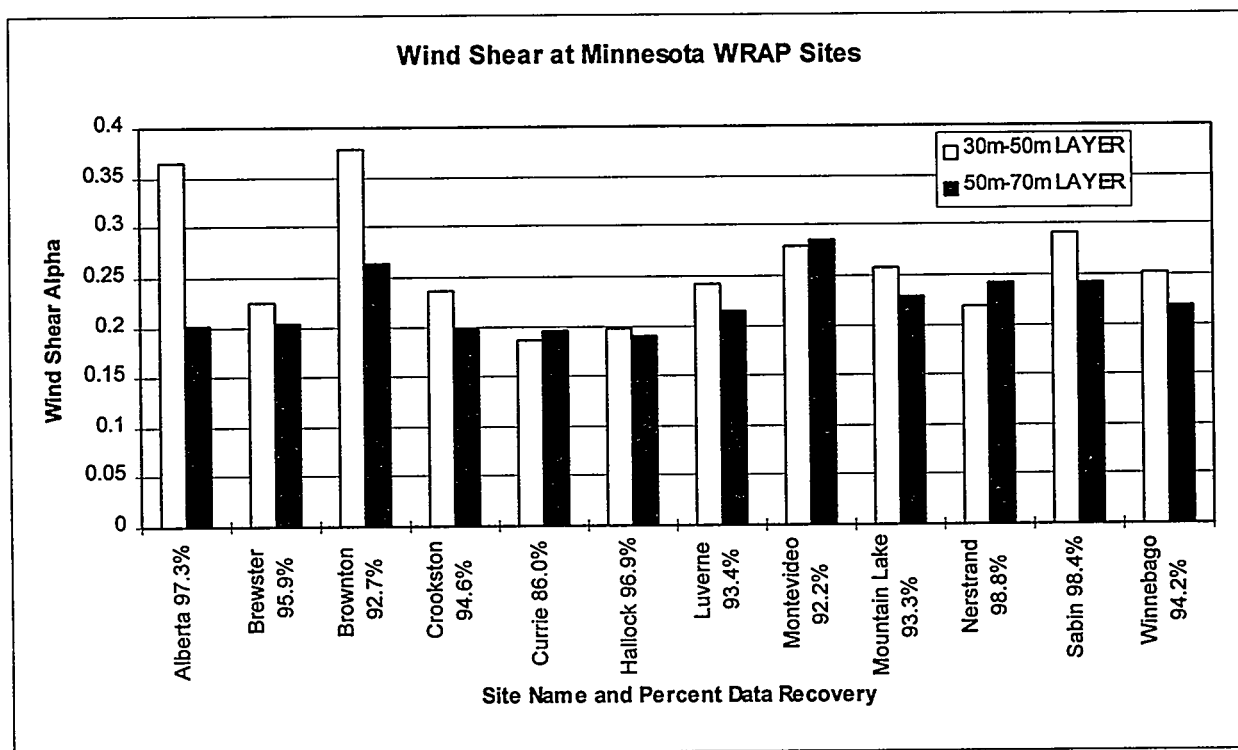


Figure 2

The wind shear alphas shown in Figure 2 do not vary dramatically from the 30-50 to the 50-70 meter layers, with the exception of the Alberta and Brownton sites. Three of the sites -- Currie, Montevideo, and Nerstrand -- have slightly greater wind shear for the upper layer, while most sites have higher wind shear values for the lower layer. Gradually reducing wind shear as heights are increased would be expected due to the reduced surface roughness effects on the wind speeds.

The large differences between the average wind shear values for the two layers at the Alberta and Brownton sites are likely due to the roughness characteristics of the countryside surrounding these sites rather than to a wind resource phenomenon. Neither the Alberta nor the Brownton sites have large obstructions near the monitoring tower. At the Alberta site the small town of Alberta is just under a mile away. At the Brownton site the surrounding countryside is changing from prairie to forest and has more wooded pockets compared to other WRAP sites to the west or south. The increased surface roughness caused by the countryside or urban development has a pronounced effect on the lower level wind speeds at these sites.

Figure 2 also indicates the overall data recovery rate for these sites. The percentages listed next to the site name is the valid data recovery rate for each site. Due to sensor icing, sensor failure, and logger failures, the percentages of valid data are less than hoped for at some sites. The winter of 1996-97 was an exceptional year relating to icing events. Several of the DPS WRAP sites were devastated by significant icing during mid-November 1996. Currie, one of the more energetic of the 70 meter WRAP

sites, needed to have all eight sensors replaced. That event and two different logger failures reduced the valid data recovery rate to 86 percent for this site. The other sites fared better than the Currie site, with many of the sites having data recovery rates in the upper 90 percent range. The Hallock site, in the far northwest corner of the state, shows an excellent data recovery rate of 97 percent, but this site was recently devastated by a late April ice storm that destroyed all sensors at the site and contributed to the flooding in that area.

To relate the wind shear to actual electrical production, it is important to see how wind shear values vary in comparison to the wind energy potential of these sites. Figure 3 shows the wind power calculated for the different levels. In comparing Figure 2 to Figure 3, it is interesting to note a trend that indicates sites with higher wind energy potential have lower wind shear values, and the lower wind energy potential sites have higher wind shear values. For instance, the Brownnton and Montevideo sites are shown to have the lowest energy, but in Figure 2 these sites had some of the highest wind shear values. Better mixing of the atmosphere takes place at sites with higher wind speeds, leading to a reduced difference between wind speeds at the different heights above ground level.

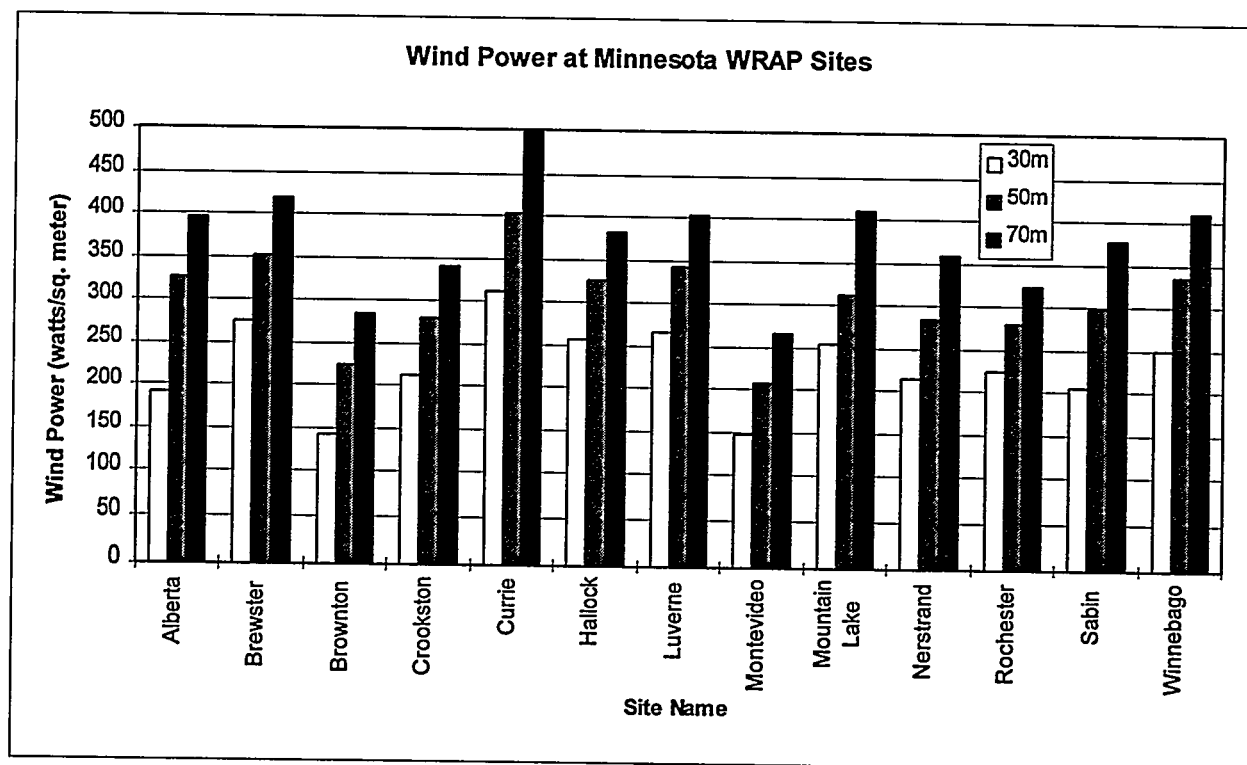


Figure 3

AVERAGE VERTICAL WIND SHEAR (TALL TOWER SITES)

The configuration of the Tall Tower sites allows for the calculation of vertical wind shear for the 10 to 30, 30 to 40, 40 to 50, 50 to 60, and 60 to 70 meter layers. The wind shear values for each of these layers were calculated in a similar fashion as for the WRAP sites. Only 10 months of data from the Tall Tower sites were available for analysis. The Chandler site experienced severe damage during a November ice storm that destroyed all sensors at the site. For the Chandler site, only about seven and a half months of valid data were available. As with the WRAP sites, the average wind shear values were calculated for wind speeds greater than 2.2 meters-per-second and considered only data marked as valid.

The average vertical wind shear for the four Tall Tower sites are shown in Figure 4. Typical shear values for wind shear between multiple levels would be in the range of 0.20, which is consistent with the values seen from the WRAP sites. As with the WRAP sites, the use of the traditional 1/7 power law for estimating wind shear tends to underestimate the wind shear effects based on the data collected thus far. This figure also lists the data recovery rate for the Tall Tower sites for the 10-month period.

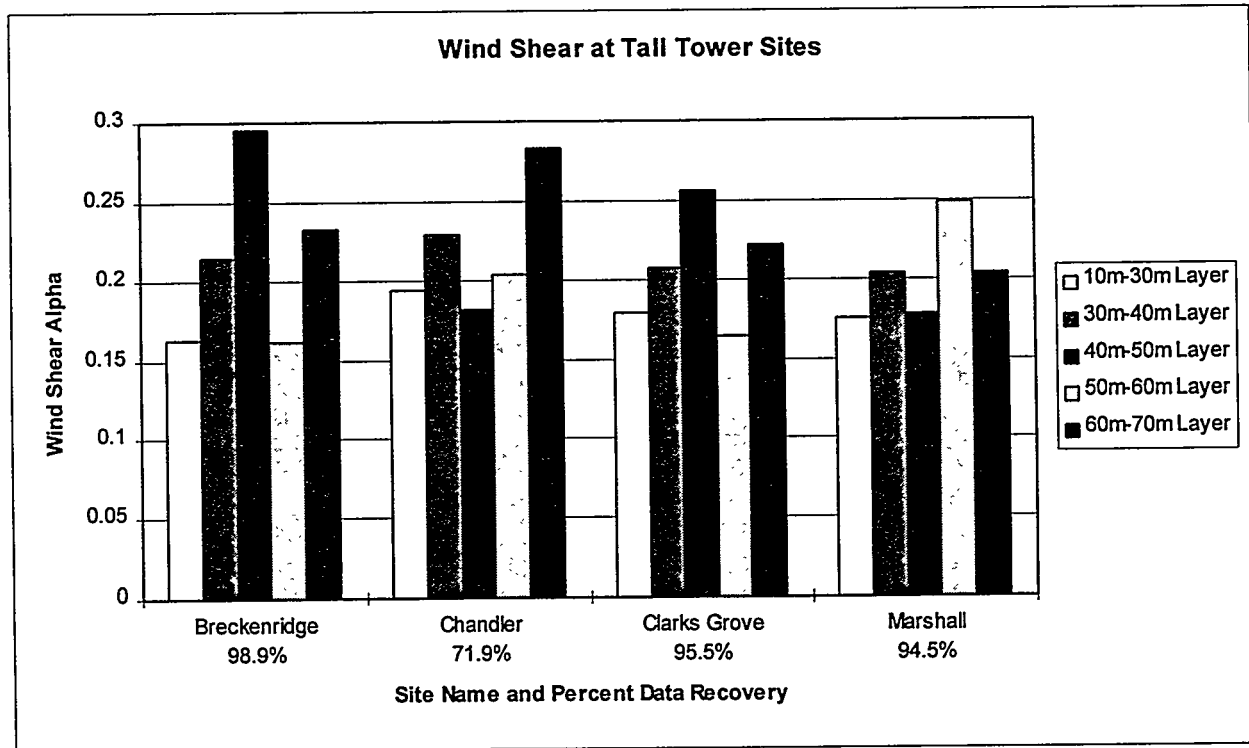


Figure 4

Figure 4 indicates there may be a significant variation in the wind shear from layer to layer. The variation in the shear values seen in this graph will need to be confirmed by additional data collection before this type of pattern can be used effectively to determine optimum wind turbine tower height. It is interesting to note that the wind shear alpha listed for Chandler at the 60-70 meter layer is significantly higher than the wind shear found at the others layers at this site. If this trend persists, there may be reasons to build towers even higher than the maximum height currently proposed -- 70 meters. Having only 7 to 10 months of data available from this project means that more data will need to be collected before these trends can be defined with any precision. The wind power at the various levels for the Tall Tower Sites has not been calculated because less than one year of data is available for these sites, requiring a number of assumptions to be made regarding the missing months of data.

DIURNAL WIND SHEAR

An additional way to analyze wind shear is by time of day. Figure 5 shows the diurnal changes in wind shear for the WRAP and Tall Tower sites for the 30 to 50 meter layer. Because 17 sites are being considered and there is no easy way to distinguish which line represented which site, no legend for this graph is included. A very consistent pattern is displayed for all of the sites for the 30 to 50 meter layer. The shear values are higher in the evening and night, with a significant drop in wind shear during the

daylight hours when the atmosphere is less stable. This diurnal wind shear pattern was also seen for these sites at the 50 to 70 meter layer. The highest line shown on this graph represents the Alberta site and the second highest line represents the Brownnton site. It was shown in Figure 2 that these sites have unusually high wind shear values for the 30-50 meter layer.

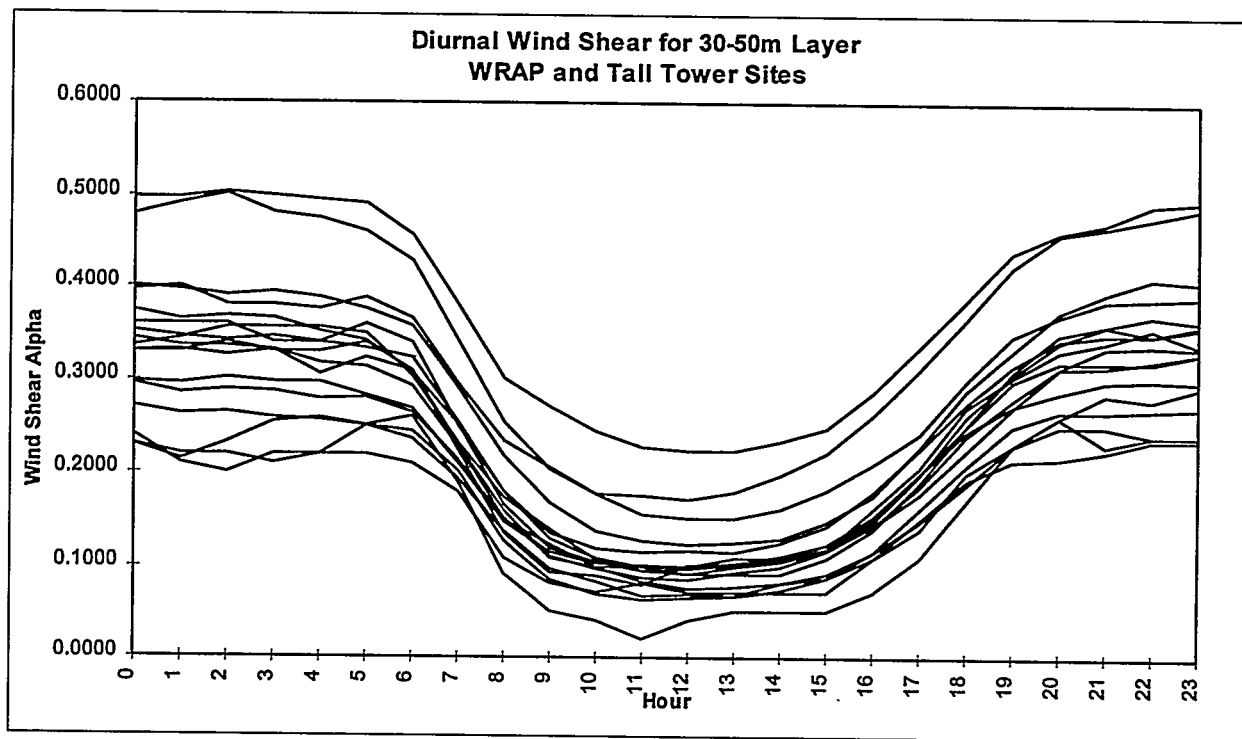


Figure 5

The diurnal wind shear pattern changes dramatically when considering only elevated wind speeds. Figure 6 is similar to Figure 5, except the diurnal wind shear has been calculated for all sites for wind speeds of 9 meters-per-second and above. The substantial mid-day dip in the wind shear values seen in Figure 5 is much less pronounced in Figure 6. This is what would be expected, since the atmosphere is more mixed during windy periods and therefore there is less difference in wind speeds from one level to another. The two upper lines shown on this graph are again for the Alberta and Brownnton sites.

DIURNAL WIND SPEEDS

The diurnal wind shear graphs above show changes in wind shear but do not provide information on the diurnal changes to wind speeds and therefore wind energy. Figure 7 shows the diurnal wind speeds for the Marshall site and provides a visual reference for the diurnal wind shear graphs. As can be seen from this graph, there is an unusual wind speed pattern at this site: the wind speeds increase significantly during the late night hours for the 60 and 70 meter levels. Generally one would expect the winds to pick up during the day as the sun warms the earth, as is the case with the 10 and 30 meter levels. At the 60 and 70 meter levels, the winds are significantly greater during the late night hours as compared to daytime hours and this is unexpected and difficult to explain. This phenomenon was originally pointed out to DPS by Ron Nierenberg, a consulting meteorologist, who had the opportunity to review some of the Chandler Tall Tower data. Most of the other WRAP and Tall Tower sites were reviewed and a similar pattern was consistently found at the 70 meter sites. This surprising diurnal pattern could have a

significant effect on how well the wind farm electrical energy matches the demand for electricity in Minnesota.

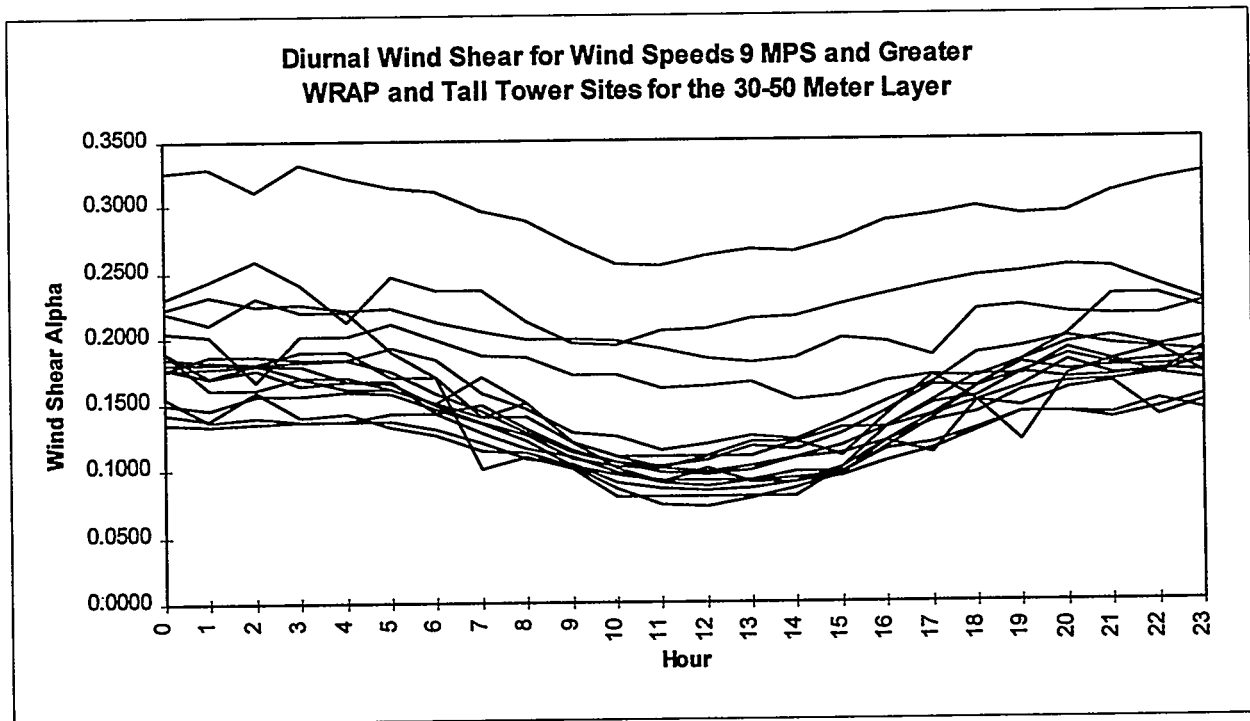


Figure 6

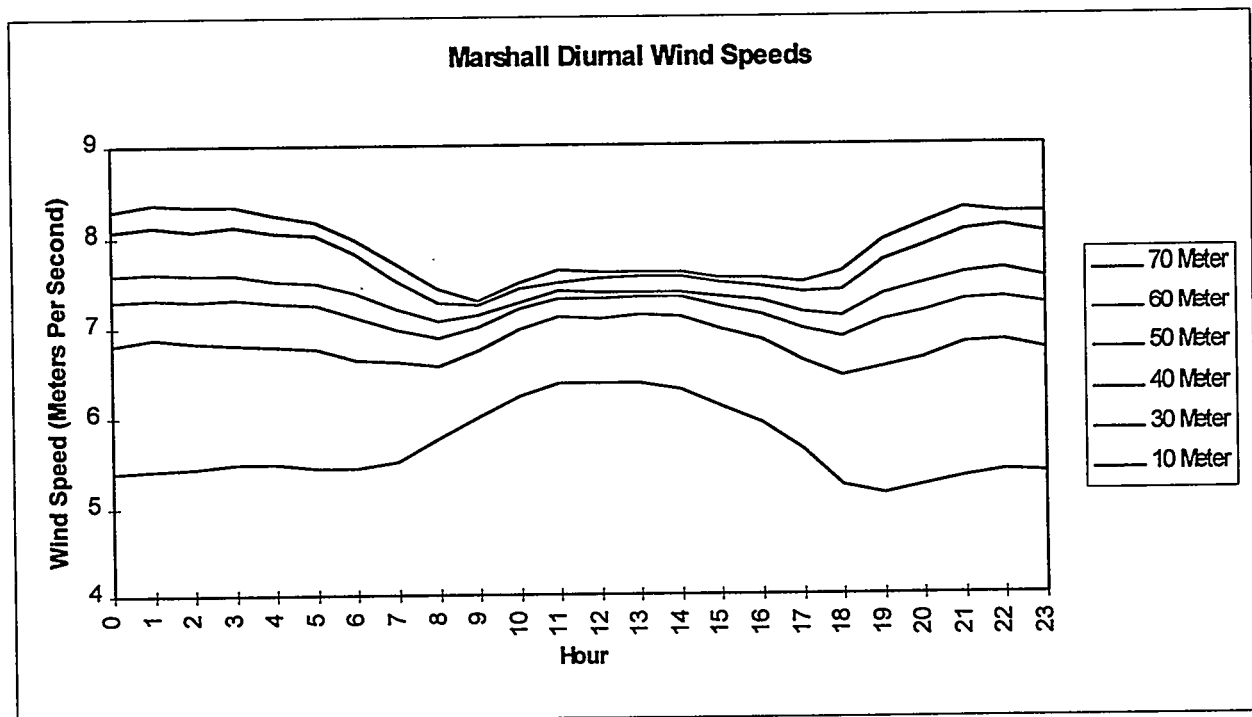


Figure 7

CONCLUSIONS

When estimating Minnesota's wind power potential for heights above the data collection level, the use of the traditional $1/7$ alpha factor will tend to underestimate the available wind power. The use of wind shear alpha factors in the range of 0.18 to 0.25 in the wind shear power equation will produce results that better represent the available wind power.

The variation in wind shear from layer to layer found at the Tall Tower sites may lead to opportunities to determine the optimum tower height design and take advantage of a more energetic wind resource "layer." Additional data collection at the Tall Tower sites will be needed before the variation from layer to layer can be well defined. Monitoring heights above the 70 meter level may need to be established to determine if the trend of increasing wind shear, shown at the Chandler site, continues or diminishes above this level. Because the Chandler site is located on the Buffalo Ridge where wind energy development is occurring, it is particularly important to monitor this site at higher levels.

The surprising phenomenon of increased wind speeds at night compared to daytime hours, at heights of approximately 60 meters and higher, may have a significant effect on how well wind farm electrical energy matches the demand for electricity in Minnesota. Previous studies comparing available wind energy and the demand for electricity relied on the wind resource data collected at a height of 30 meters. The 30-meter data had a vastly different diurnal profile than has been now found at 60 and 70 meter heights. Because wind turbines with a hub height of 70 meters are being proposed for the Buffalo Ridge in Minnesota, it will be important to compare wind energy availability and demand for electricity based on data collected at the 70 meter level.

ACKNOWLEDGMENT

Minnesota Department of Public Service engineering interns Julie Choi and Greg Trende, contributed to the work reported here by performing extensive data analysis.

A MODEL TO PREDICT THE POWER OUTPUT FROM WIND FARMS

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ABSTRACT

This paper will describe a model that can predict the power output from wind farms. To give examples of input the model is applied to a wind farm in Texas. The predictions are generated from forecasts from the NGM model of NCEP. These predictions are made valid at individual sites (wind farms) by applying a matrix calculated by the sub-models of WASP (Wind Atlas Application and Analysis Program). The actual wind farm production is calculated using the Risø PARK model. Because of the preliminary nature of the results, they will not be given. However, similar results from Europe will be given.

1 INTRODUCTION

In recent years a need has emerged to have models which for the next day or two can reliably predict the power produced by wind farms. This is due to the fact that there now are many areas where the penetration of wind power is so significant that the electrical utilities must take the wind-farm-produced power into account in its daily planning and dispatching. In many areas in Denmark for instance, the penetration can reach as much as 20% at certain times.

With the abilities of present day numerical weather prediction (NWP) models it is now possible to accomplish this task; this was shown in Landberg et al (1993). The concept of using NWP model output has also been used in Barbour and Walker (1995). The economic value of using these forecasts has been assessed in Watson et al (1994) and Milligan (1995).

This paper will describe a first US application of a model developed and tested (on-line) for a number of grid-connected wind farms in Denmark (cf Landberg, 1997a and Landberg et al, 1997). The model uses output from the NWP model of the National Meteorological Center. The predictions are used in 6-hourly steps and the look-ahead horizon of the model is 48 hours.

2 THE METHOD

The method for predicting the power output of a wind farm is outlined in Figure 1. The idea is to explain (ie use physical models) as much as possible. This is done by modelling the large-scale flow by a NWP model. As we zoom in on the site – using the geostrophic drag law and the logarithmic wind profile – more and more detail is required, this detail is provided by the WASP program (Mortensen et al, 1993). To calculate the total production of the wind farm, taking the shadowing effects of the turbines into account the PARK program (Sanderhoff, 1993) is used. Finally, to take any effects not modeled by the physical model and general errors of the method into account a model output statistics (MOS) module is used. For a more detailed description of

the model, see Landberg and Watson (1994) and Landberg (1997a). For an equational look at the model, see Landberg (1997b). In the US case the National Center for Environmental Prediction (NCEP) Nested Grid Model (NGM) is used and in the European the HIRLAM model of the Danish Meteorological Institute (cf Machenhauer, 1988).

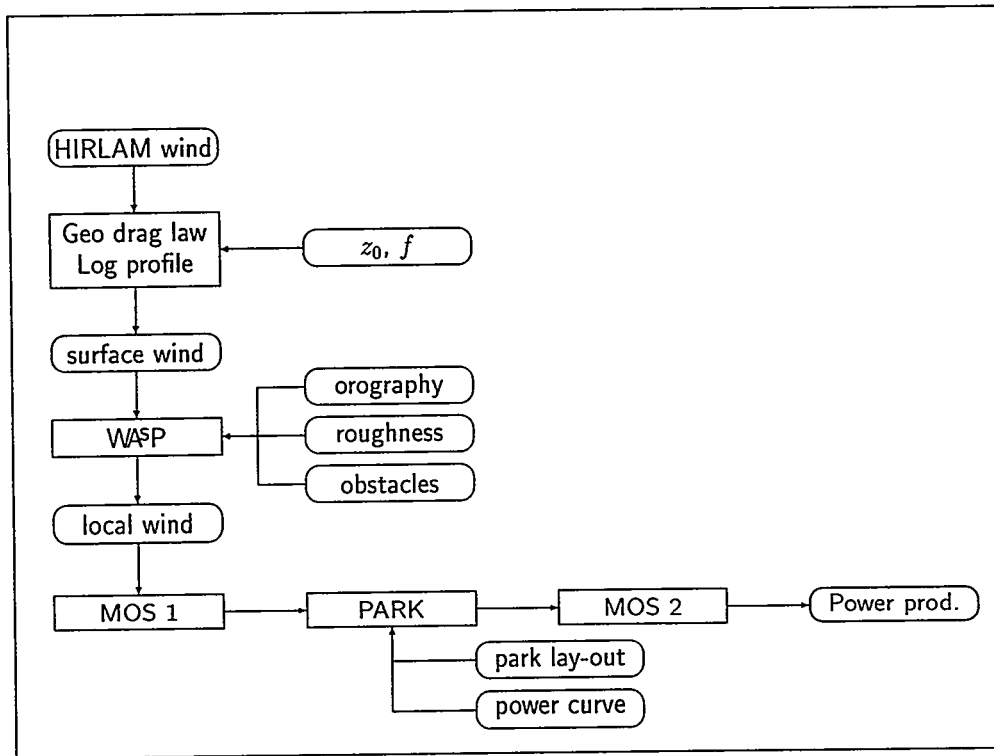


Figure 1: Flow chart of the prediction model. In the US case the HIRLAM wind is replaced by the NGM one.

3 INPUT TO THE MODEL

To be able to predict the power output of a wind farm the following input is needed:

- NWP wind field (Geo. drag law)
- description of orography (WASP)
- description of roughness (WASP)
- description of obstacles (WASP)
- power curve (PARK)
- thrust curve (PARK)
- wind farm lay-out (PARK)
- measurements of actual power production (MOS)

Note that this information, except for the NWP forecast and the measurements, is needed only for the initial analysis of the wind farm; once the farm is analysed, the prediction model uses only the results of the analysis. For an example of the analysis of a wind farm, see the Texan case-study

below.

4 OUTPUT FROM THE MODEL

For ease of electronic transfer, the model predictions are given as HTML-files. The advantage of this is that if the utility is big enough it can run the model at its own premises and view the HTML-files internally. If a number of small utilities have joined together they can view the pages via the Internet. The files contain the 12 forecasts (from +3 to +36 hours ahead) for the total production (if applicable) and for each wind farm. It is imagined that the utility then have a program (ie a Web-browser) which displays the forecasts. An example of a prediction is given in Figure 2.

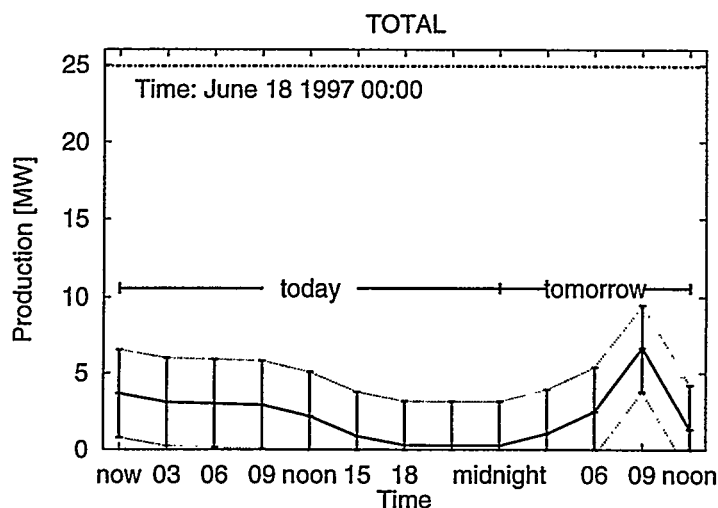


Figure 2: Example of the forecasts as could be seen at the dispatchers desk. The figure shows: the total rated power (dot-dash line at the top), the prediction (solid line), and the expected error (dotted line on both sides of the prediction). The plot is originally in colour.

5 OPERATIONAL SET-UP

The model has been running on-line since the beginning of the year (ie for more than five months), predicting the production for a great number of wind farm located in Denmark, Great Britain and Greece. The predictions are taken from the GRV and GRD versions of the operational HIRLAM model at the Danish Meteorological Institute, cf Figure 3. These are sent via the Internet to Risø. At Risø a system is set up that runs the power prediction model every time a new HIRLAM forecast arrives. The output from this model is HTML files which are put on the Internet automatically. The HIRLAM model run is available around 3-4 hours after its verify time, the time in transit between DMI and Risø is insignificant, and the power prediction model is run in less than a minute. The HIRLAM model is run twice a day, so, the Web-page is also updated twice a day with a new 36-hour forecast. The latest development is that the HIRLAM prediction horizon has been extended to 48 hours.

In the US case no on-line system was set up, since this is a first demonstration. In principle, however, a system similar to the one set up in Europe could be implemented without any difficulty.

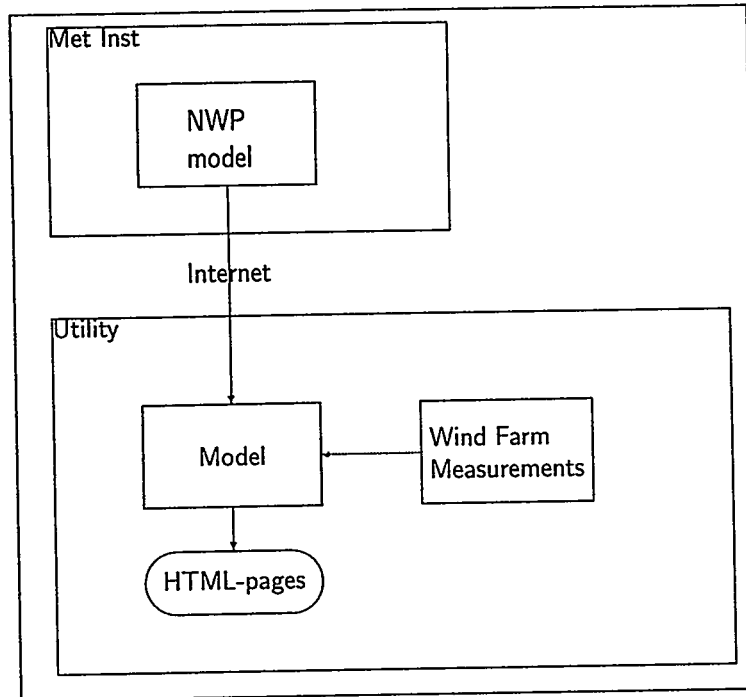


Figure 3: The operational set-up. From the Meteorological Institute where the predictions are made, via the Internet, to the utility, where the power production model is run. Presently, the measurements are not input to the model on-line, see Section 8, however. The HTML-pages can be viewed by any Web-browser, eg Netscape or Internet Explorer.

6 TEXAS CASE STUDY

In this section the model described above will be applied to the Central and South West Services Small Wind Farm, Fort Davis, Texas. The model will be used to predict wind speed, since power production data was not available simultaneously with NGM forecasts. In the following the site will be described briefly, the results of the WASP-analysis will be given, and the NGM output will be described.

6.1 The site

The site is located in the western part of Texas, cf Figure 4. Two masts have been erected at the wind farm site, one (mast 1) measuring at 10, 30, and 40 m agl and one (mast 2) at 10 m agl, cf Figure 5. Measurements have been taken every hour (10 minute averages) from October 1993 to April 1995. In the following analysis the 40-metre data from mast 1 has been selected as the ones the predictions are made for. The orography has been provided by EPRI (digitised by CompuSyst) and the roughness for the entire area has been set equal to 0.05 m.

6.1.1 WASP-analysis

The Risø National Laboratory WASP program (Mortensen et al, 1993). is used to calculate the influence of the local corrections due to orography and roughness. These corrections are given in

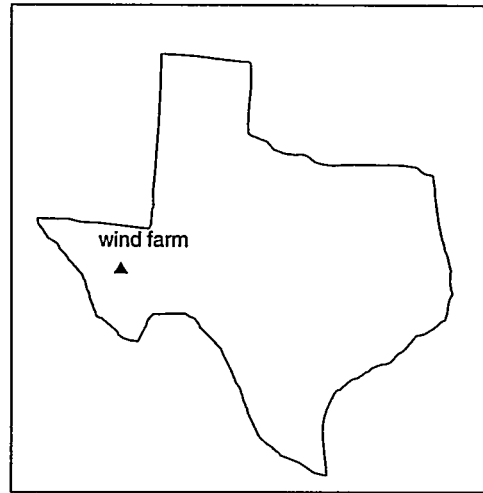


Figure 4: Location of the wind farm site.

Table 1.

Table 1: The result of the WASP-calculation for mast 1 at 40 m agl. The results of the three sub-models are given: As can be seen only orographic corrections are found necessary. Each row represents a sector. A value of 0 means no correction. The column labelled 'Meso z_0 ' is the meso-scale roughness used in the geostrophic drag law.

Sect	Obstacles		Roughness		Orography		Meso z_0
0	0.000	0.000	0.000	0.000	32.598	3.645	0.0500
30	0.000	0.000	0.000	0.000	43.661	4.202	0.0500
60	0.000	0.000	0.000	0.000	50.576	0.797	0.0500
90	0.000	0.000	0.000	0.000	47.145	-3.284	0.0500
120	0.000	0.000	0.000	0.000	36.366	-4.427	0.0500
150	0.000	0.000	0.000	0.000	28.689	-0.933	0.0500
180	0.000	0.000	0.000	0.000	32.598	3.645	0.0500
210	0.000	0.000	0.000	0.000	43.661	4.202	0.0500
240	0.000	0.000	0.000	0.000	50.576	0.797	0.0500
270	0.000	0.000	0.000	0.000	47.145	-3.284	0.0500
300	0.000	0.000	0.000	0.000	36.366	-4.427	0.0500
330	0.000	0.000	0.000	0.000	28.690	-0.933	0.0500

6.2 NGM predictions

The NGM predictions have been provided as grid-point values. The distance between the grid points is 1.5° (approx. 150 km (94 mi)) for N-S as well as E-W. As a comparison the Danish HIRLAM model is now down to around 50 km (32 mi) for the version covering the Atlantic and parts of Russia (ie an area of similar size). The grid-points are located as shown on the map, cf Figure 6. As can be seen the minimal distance to the site is around 0.5° , so the model was tested with the data from the six nearest grid points as input.

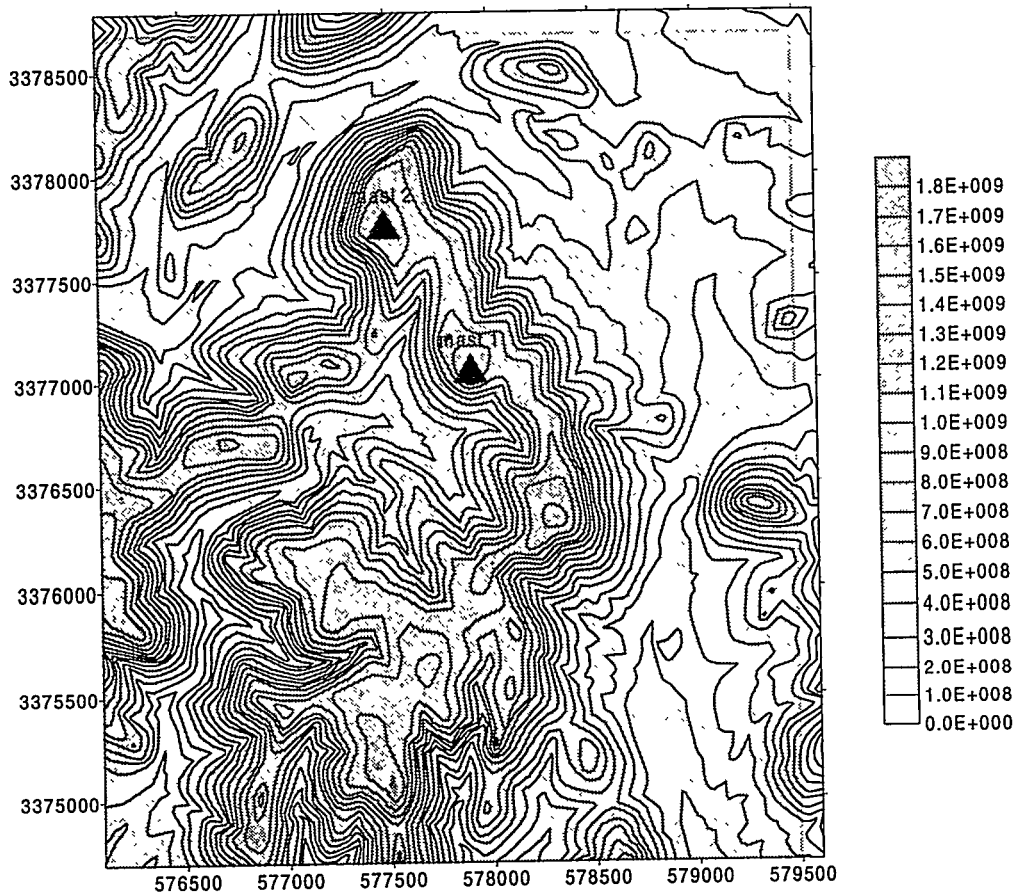


Figure 5: The location of the two masts (marked by triangles) on the CWS wind farm site in Texas. The lines on the map are contour lines, and the shading is the annual production (in kWh, key to the right) of the 600 kW machine, using data from the 40-metre measurements at mast 1.

7 COMPARISON WITH DANISH CASE

To put the preliminary results of the US case into a frame of reference, the results from a case study carried out in Denmark will be given in the following. In this case study 17 wind farms were modeled for a whole year (Feb 1995–Jan 1996), cf Landberg et al (1997). One of these wind farms (Kyndby, Zealand) will be used for the comparison. The wind farm consists of 21 180 kW turbines and is located near the shore of a fjord. The performance for the one-year period is shown in Figure 7.

To get an estimate of the skill of the model the predictions are compared to those of the *persistence* model, which is a very simple model stating that

$$P(t + \ell) = P(t) \quad (1)$$

where $P(t)$ is the production at time t and ℓ is the look-ahead time. This model could popularly be called the ‘what-you-see-is-what-you-get’ (WYSIWYG) model!

It can be seen from this that in the first four hours the persistence model performs better than the

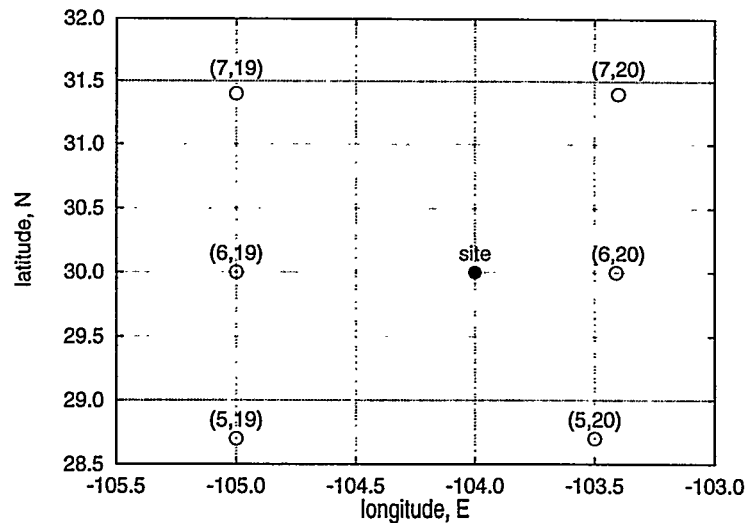


Figure 6: The grid of the Nested Grid Model. The six grid-points nearest to the site as well as the site itself are shown.

developed model, after that the model is superior. It can also be seen that – as was the case with the model predicting the wind only, cf Landberg and Watson (1994) – that the mean absolute error (ie the scatter) seems to be rising only very slowly with look-ahead time.

8 THE COMBINED MODEL

The above results show that the physical model does not perform very well (compared to persistence) in the near-term, ie up to 4–6 hours ahead. It is well known, however, that statistical models (cf Jensen et al, 1994, Madsen, 1996 and Nielsen and Madsen, 1996) which base themselves on the measured wind farm production do indeed perform well in this time window. An obvious conclusion is to combine these two model approaches. This is what is presently being done in the JOULE III project in a co-operation between Risø and the Institute for Mathematical Modelling (IMM) at the Technical University of Denmark: the physical model based on NWP model forecasts is combined with the statistical model based on the measurements. The results are very preliminary, but show that it is indeed possible to make a model, which predicts well in the near-term as well as the long-term.

9 DISCUSSION

One can speculate how far into the future the stability of these predictions holds, is it 48 hours or even further. There is no doubt that there is an upper limit: at some point all initial information in the model domain will have been ‘blown out’ of the domain. Theoretical estimates give that NWP models will be able to predict as far ahead as three days (72 hours), this demands, however, that the model domains are global.

The model can be improved in a number of ways: firstly, as already mentioned, by including on-line measurements from the wind farms, secondly, improvements of the accuracy of the NWP models

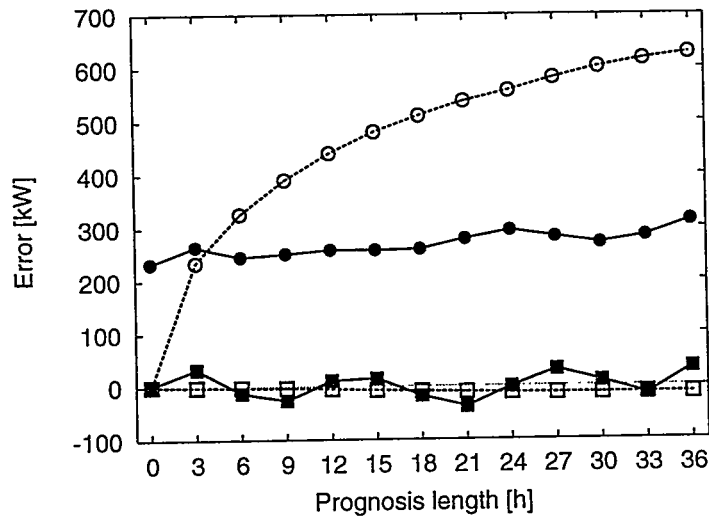


Figure 7: Plot showing the performance of the model described here, compared to the persistence model for the Kyndby wind farm using a full year's worth of data. The rated power of the wind farm is 3.78 MW, ie the error never exceeds 10% of the rated power. Filled symbols and solid lines refer to the model and open symbols and dashed lines to persistence. Round symbols are the absolute mean of the error (in kW) and square symbols are the mean error (also in kW). The forecast length (in hours) is along the x -axis.

will also improve on the prediction. The present bottle-neck is the accuracy of the NWP models, since the transformation to the surface is quite accurate.

10 SUMMARY

This paper has described a model that predicts the wind-power-produced energy up to 48 hours ahead. The model was used to predict the power for a wind farm in Texas. The model is based on forecasts from the National Center for Environmental Prediction (NCEP) Nested Grid Model (NGM). These forecasts are made valid locally by using the WASP program. The power curve is used to calculate the production and reductions because of wakes from other turbines are calculated using PARK. An example of the performance of the model applied to a wind farm in Europe was given.

ACKNOWLEDGEMENTS

The data from the Texan wind farm was kindly provided by Central and South West Services.

The development of the model has been funded by the EFP-programme under the Danish Ministry of Energy and the Environment, contract number 1363/94-0005 and is presently funded by the JOULE III programme of the Commission of the European Communities, contract JOR3-CT95-0008.

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WIND FARM ARRAY WAKE LOSSES

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ABSTRACT

A wind turbine wake study was conducted in the summer of 1987 at an Altamont Pass wind electric generating facility. The wind speed deficits, turbulence, and power deficits from an array consisting of several rows of wind turbines is discussed. A total of nine different test configurations were evaluated at for a downwind spacing ranging from 7 rotor diameters (RD) to 34 RD and a cross wind spacing of 1.3 RD and 2.7 RD. Wake power deficits of 15% were measured at 16 RD and power losses of a few percent were even measurable at 27 RD for the closer cross wind spacing. For several rows of turbines separated by 7-9 RD the wake zones overlapped and formed compound wakes with higher velocity deficits. The wind speed and direction turbulence in the wake was much higher than the ambient turbulence. The results from this study are compared to the findings from other similar field measurements.

INTRODUCTION

Wind farm development occurred very rapidly in California beginning in the early 1980's. The limited wind information that was available was used to the fullest to site turbines and make energy projections. There was little measured information available on the impact of turbine wake speed deficits on downwind machines and most theoretical and measured studies generally suggested that beyond 10 RD the wake velocity deficits should be minimal behind a single machine. In hilly topography it was felt that the wakes would be eroded rapidly by the well mixed winds and the natural variation in the micro scale winds would dominate the power production. Thus, the typical row spacing of the turbines was on the order of 8-10 RD and the cross wind spacing generally was 1.5-2.0 RD. Quite often the downwind spacing was dictated by where the next available ridge line was located. It became apparent that after some of the wind farms became operational that energy production was lower than expected. It was felt that some of the energy shortfall was due to wind farm array wake losses. To better understand the impact of upwind machines on those downwind, U.S. Windpower (USW) designed and performed some special tests on a group of USW 56-100 machines in the late summer and fall of 1987.

TEST DESCRIPTION

The configuration of the four rows of turbines, labeled A-D, are shown in Figure 1. The turbines are downwind operating and have a variable pitch. The prevailing wind direction is southwest. The turbine rows are oriented normal to the prevailing flow and are separated by 18, 9, and 7 RD.

The cross wind spacing is 1.3 RD. The turbines are located on a gently rolling plateau and the machines in Rows A & B are about 9m (30 ft) higher in elevation from those in Rows C & D. All of the turbines have the same hub height, 18.3m (60 ft).

Several wind speed and direction sensors were mounted on meteorological towers up wind of the four rows. Climatronics sensors were positioned on the top of 30.5m (60ft) towers at locations Mb, Mc, and Md in Figure 1. A WeatherMeasure cup and vane anemometer was placed on top of a 14.3m (47ft) mast at site Ma. Power transducers were connected to four of the turbines, each immediately down wind of the meteorological towers. The data were collected on Campbell Scientific CR-21X data loggers. The data loggers sampled each channel once every 10 seconds and 30 minute averages of wind speed, direction, power, and the standard deviation of these parameters were stored. The data were collected at the same time, frequency and averaging interval as the wind farm power information.

A test plan was devised with assistance from the wind farm operations personnel. Machines were turned on and off for the various configurations and sufficient data were gathered to get meaningful results. A detailed test plan was created and updated frequently depending on the success of the on going tests. Based on the wind direction, time of day, and turbine power levels the operators were given instructions on what configurations to initiate or abort. The majority of the testing was done for wind speeds below rated power output ($<14\text{m/s}$ (31mph), and a power range of 60-100 % of rated output). Over 180 hours of data were used in the analysis.

DATA ANALYSIS

For each 30 minute data set the average power output was calculated for each row. For Row A the mean power level was computed using all of the machines. When Row A was turned off, the fifth machine from the north end of the row was left on so the mean power from the row could be estimated. The mean power from Row B was calculated using the power output data for five of the six turbines in the row. The northernmost turbine in Row B operated intermittently so data from this machine were not used. When Row C was waked out by Row B, the Row C power level was computed as the lowest power output machine in the row. Similarly, the lowest power output of the machines in Row D was used when this row was waked out by the upwind row(s).

Choosing the lowest production machine in a row under upwind wake conditions would give the worst case wake power loss estimate. Each row was also run with no upwind turbines operating to establish the free air background power (wind speed) relationships between turbines. Natural background power or velocity deficits were subtracted from the wake measured deficits to derive the true power (velocity) deficits.

To determine the power losses due to wake interaction, the power ratios were calculated by comparing the power output of the downwind row to the power level of the upwind (non-waked) row. Power Ratios were calculated using three different reference locations. The reference points were the mean power level for Row A, the mean power level for Row B, and the power output of the northern most turbine on Row C (this turbine was not in a waked zone under southwest winds). The background power (velocity) ratios for Rows B-D were calculated by turning off the upwind rows and comparing the measured power (velocity) levels to the reference locations. The background measurements indicated the natural spatial variation of the wind in the test area would result in Row B generating 90% of the power of Row A, Row C would generate 89% of the power of Row B, and Row D would produce 86% of the power of Row B if there were no upwind rows of turbines operating. This same methodology was used to calculate the wake velocity ratios

(deficits) using the speed data from the three meteorological towers, Mb, Mc, and Md. The speed ratios were computed with respect to the speeds at Site Mb. The wind directions measured at Sites Mb and Md were used to determine if there was wake zone interaction

DISCUSSION OF THE FINDINGS

Wake Power Deficits

The growth rate and downwind decay of the wake is governed by the drag of the blade (Thrust Loading) and the ambient turbulence level. For a given turbine Thrust Loading (wind speed level) in turbulent, well mixed conditions, the wake will be re energized quickly by stronger winds from outside of the wake. The wake zone will dissipate much more rapidly than under stable non turbulent conditions. Thus, the ambient turbulence level plays a key role in the downwind structure and persistence of the wake zone. Turbulence Intensity (TI) is often the measure of the turbulence level. TI is defined as the standard deviation of the wind speed divided by the mean speed. The following discussion looks at the wake power losses (and speed deficits discussed in the next section) in context of a given speed range of 10-12 m/s, which is below the rated output at 13.5 m/s.

The Power Ratios calculated for each row of turbines for the nine configurations were used to calculate the wake power losses. For example, the mean Power Ratio between Row B and Row C (9 RD spacing) when Row A was not operating was 0.63 using the Power Ratio at Site B as a reference. The background ratio for Row C was 0.89. Dividing 0.63 by 0.89 yields 0.71, or the wake power loss at Row C is 29% at 9 RD spacing. The wake power losses in percent using the three different reference locations are given in Table 1. Most of the calculated losses are in good agreement using the three different reference locations. The Row B reference ratios are more consistent and thus probably give more reliable results.

Power loss as a functions of downwind distance (RD) and cross wind spacing is graphically displayed in Figure 2. These losses are for wind speeds in the 10-12 m/s range and a TI of about 10%. The plotted data are for the wake losses based on Row B as a reference. The two curves drawn represent the average power losses for a cross wind spacing of 1.3 and 2.7 RD. Power losses for 1.3 RD cross wind spacing are 25-35% at 10 RD downwind. Even at 16-18 RD the losses are in the 15-18% range. It appears that the power losses become negligible for downwind distances of greater than 25 RD. When the cross wind spacing is opened up to 2.7 RD, the wake deficit power the power losses decrease by about a factor of two, and the loss is less than 5% at 20 RD. It is estimated that the uncertainty of the loss estimates is on the order of plus or minus 3%, based on the differences between the ratio estimates.

It was observed that when there were two rows of operating machines upwind of a third row that the combined (and an enhanced) wake zone from the upwind rows was detected at the third row. When Rows B, C, and D were running, the Row D power loss was 51% (16% higher than when only Row C and D were on). This combined wake zone loss was also measured when Rows A and B waked out Row C. The wakes from closely spaced rows of turbines overlap and the speed deficits are additive. Also, when the cross wind spacing is tight, the horizontal mixing of the air which helps reenergize the wake, is diminished, so the wake will be felt further downwind. Under more stable flow conditions, which typically occur with Altamont Pass winds, mixing is further reduced. The combined effect of additive wake speed deficits and low ambient turbulence levels results in power losses being felt much further downwind.

Figure 2 also contains data from other wake power loss studies taken from behind a single turbine and within wind farms with various cross wind and downwind configurations. The power losses are for speeds in the 10-12 m/s range. Elliot, et al. (1988) reported that the power loss of the a 60m diameter turbine at Goodnoe Hills, WA 6.7 RD downwind of a similar machine was 28% for TI values <5%. The loss decreased to about 17% for TI values in the 5-10% range and when the TI was 10-15% the power loss was 10%. Wind farm wake array power losses behind multiple rows of turbines have been measured at several locations. Nierenberg (1990) performed wake deficit tests in the Altamont Pass for machines spaced at 1.9 by 8 RD. At 8.5 RD the maximum power loss was 16% and it decreased to 10% at 17 RD. When 2 rows of turbines were operating upwind of a third row the power loss of the third row increased by 50%. Wake power loss measurements were taken by Wei, et al.(1990) at a wind farm in Hawaii consisting of three rows of 250 kW Mitsubishi turbines spaced 1.5 by 10 RD and 1.5 by 13 RD. At 10 RD the power loss was 24% and at 13 RD it was 21%. When the 2 upwind rows were on the third row loss increased from 21% to 29% (compound wake). Turbulence information was not reported for the tests in Hawaii but a characteristic nature of the trade winds is low turbulence. The wind shear from the 28-40m level was high as the simple power law exponent (α) varied between 0.25-0.35 during the tests. Stable, non-turbulent flow and high wind shear is typical in trade wind regimes and such wind characteristics inhibit the wake from dissipating rapidly downwind. The result is significant power (and energy losses) in downwind turbines, which has been the case in Hawaii.

For a select data set when Rows B, C, and D were running, the power losses for Rows C and D were calculated as a function of the TI. For wind speeds at Site Mb of 10.7-11.6 m/s (24-26 mph), the power loss for Rows C and D are plotted against TI in Figure 3. As the TI increases the wake power loss decreases rapidly for both downwind rows of machines. Row C is 9 RD downwind of Row B and the average Power Loss shown in Figure 2 is 30%. Figure 3 shows that under low turbulence levels this power loss can increase to near 40% and when the TI is greater than 0.20 the power loss will decrease to below 20%. Similarly, Row D, which is subjected to compound wakes, has a very high power loss (>70%) for low TI levels and the power loss decreases to near 50% for high turbulence levels.

Measured Wind Speed Deficits in Wake Zones

Speed deficits were calculated for Sites Mb, Mc, and Md. The wake speed deficits were computed for Mc and Md using Mb as a reference using the same methodology as was used to calculate the Power Deficits. The anemometer sites are located downwind of the turbines by 6.2 RD (Md) and 7.7 RD (Mc). The distance of Mb from Row B is about 14 RD. Deficits were calculated when the Mb speeds were in the 9.4-10.7 m/s (21-24 mph) and 10.7-12.5 m/s (24-28 mph) range. The deficits for both speed ranges were very similar. The background relationships indicated that the Speed Ratio of Mc to Mb was 0.98 and Md to Mb was 0.96.

The wake wind speed deficits for 1.3 RD and 2.7 RD cross wind spacing are plotted in Figure 4 as a function of downwind distance. The wake speed deficits decrease with downwind distance and at 14 RD they are 8% (1.3 RD cross wind spacing). This speed deficit relates to about a 20% power loss as shown in Figure 4. Beyond 14 RD the curve was estimated and the zero point was chosen at 29 RD where the wake power loss went to zero (reference Figure 3). The wake speed deficits are much lower for a 2.7 RD cross wind spacing. Compound wake speed deficits from two upwind rows of turbines were calculated and the points are shown in Figure 4. When Rows B and C were operating, the wake speed deficit at Md was 24% compared to 19% when only Row C was

on. A similar increase in wind speed deficits was reported by Adams (1996) when two upwind rows of turbines were operating. These deficit points are plotted in Figure 4. For two rows of machines spaced at 5 RD by 8 RD the 7 RD downwind deficit increased from 18 to 23% (Adams). These machines are located along the sea in the northern part of The Netherlands at Sexbierum. Wake deficits measured at the Hawaii wind farm indicated an 11% speed deficit at 10 RD downwind behind a row of Mitsubishi machines spaced 1.5 RD apart. The speed deficit at the third row when two upwind rows were operating was 18%. The row separation upwind was 10 RD and 13 RD.

Figure 4 also shows the wake speed deficits measured behind a single machine (Baker, et al., 1985, and Elliot, et al, 1988). The measurements were taken downwind of the 91.5 m (300 ft) diameter MOD-2 turbine. The single machine deficits decrease much more rapidly and reach a zero value at 12 RD. The difference between the single machine and the wind farm curves can be explained by the additional speed deficits caused by the overlap of wakes from closely spaced machines.

Wake Turbulence Levels

Wind speed and direction turbulence was analyzed from the data gathered at Sites Mb, Mc, and Md when the three rows (B, C, & D) of turbines were on and off. For southwest winds in the 9.4-12.5 m/s (21-28 mph) range, the wind speed TI was calculated for the three sites and the standard deviation of the wind direction, sigma theta, was analyzed at Sites Mb and Md.

The mean TI values at Mb were compared to the turbulence values calculated in the wake zone at Mc and Md. There is a significant increase in the TI in the wake zone as shown in Figure 5. The percent increase is largest for the 1.3 RD cross wind spacing. At 8 RD downwind the TI increased by 14% and at 14 RD the increase was 6%. When two upwind rows were on there was a 22% increase in the TI at Md, located 6 RD downwind from row C. When all of the machines were off the turbulence values at all three measurement sites were similar. Adams (1996) reported higher increases in the TI due to wakes at the Sexbierum wind farm. At 7 RD in the single wake case the TI increase was 33% and in the double wake study the increase was 27%. An increase in the turbulence of 50% was measured by Elliot (1988) at 8.3 RD behind a single turbine. It is apparent that there is a substantial increase in the TI values in wake zones, but the reported magnitudes of the increase vary greatly.

The directional turbulence (standard deviation of direction) was measured at Site Md when the machines were on and off. Frequency distributions for both operating conditions are shown in Figure 6. When the turbines were off the mean standard deviation of the wind direction was 5.3 degrees, and the value doubled to 10.7 degrees when the machines were running. Also, the scatter of the values increased by about 70% when the turbines were operating. The increase in the directional turbulence by a factor of two in the compound wake is much greater than the increase in the speed TI, which showed a 22% increase. This indicates that there will likely be a significant increase in the yaw activity of turbines caught in heavy wake areas, which could lead to premature yaw system failures. Measured fatigue loads due to wakes are discussed by Adams (1996).

CONCLUSIONS

The wake wind speed deficits, turbulence levels, and power deficits were very high for the tightly spaced array of turbines studied. For a 1.3 RD cross wind spacing power losses for machines 20

Rd downwind could be 10% for wind speeds below rated output. If the cross wind spacing is increased by a factor of two the losses decrease by over 50% and the wake turbulence levels are greatly reduced. When turbines are closely spaced in the cross wind direction the wakes will overlap creating an enhanced speed deficit zone that can be felt much further downwind. Turbines immersed in heavy wake zones not only are subjected to significant power losses but also to high levels of horizontal wind direction variation which will lead to increased yaw activity and possibly premature yaw system failure. The ambient turbulence level is a major contributor to eroding the wake. Sites that have higher ambient turbulence levels can expect to see the downwind wakes decay much more rapidly than lower ambient turbulence sites, like Altamont Pass.

ACKNOWLEDGEMENTS

Many people at Kenetech Windpower (formerly USW) were instrumental in making the field measurement program a success. In particular the meteorological technicians and those in wind farms operations provided excellent support. The authors were employed at USW at the time of the work. We are indebted to Kenetech for releasing the information for publication.

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Table 1 Summary of the Average Power Losses for the Three Reference Locations

<u>Spacing (RD)</u>	<u>Ratio to Pa</u>	<u>Ratio to Pb</u>	<u>Ratio to Row C Turbine</u>
1.3 x 7	35%	35%	30%
2 upwind rows on	51%	51%	48%
1.3 x 9		29%	27%
2.7 x 9		14%	
1.3 x 16	18%	15%	19%
2.7 x 16	15%	8%	8%
1.3 x 18	15%		11%
2.7 x 18	6%		9%
1.3 x 28		3%	0%

FIGURE 1 WAKE TEST CONFIGURATIONS

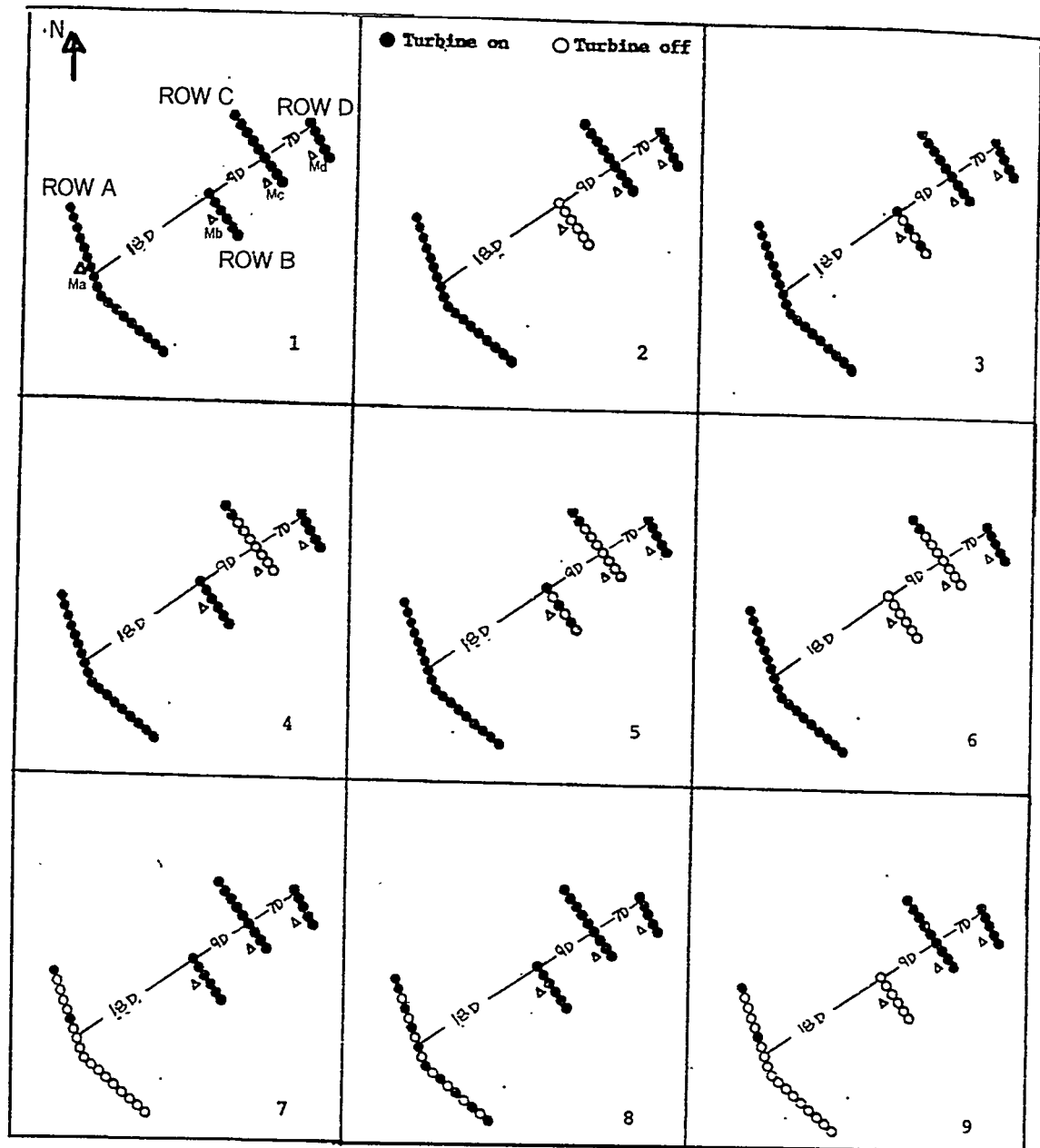


FIGURE 2 WAKE POWER LOSS VERSUS DOWNWIND DISTANCE AND CROSSWIND SPACING (WIND SPEED 10-12 M/S)

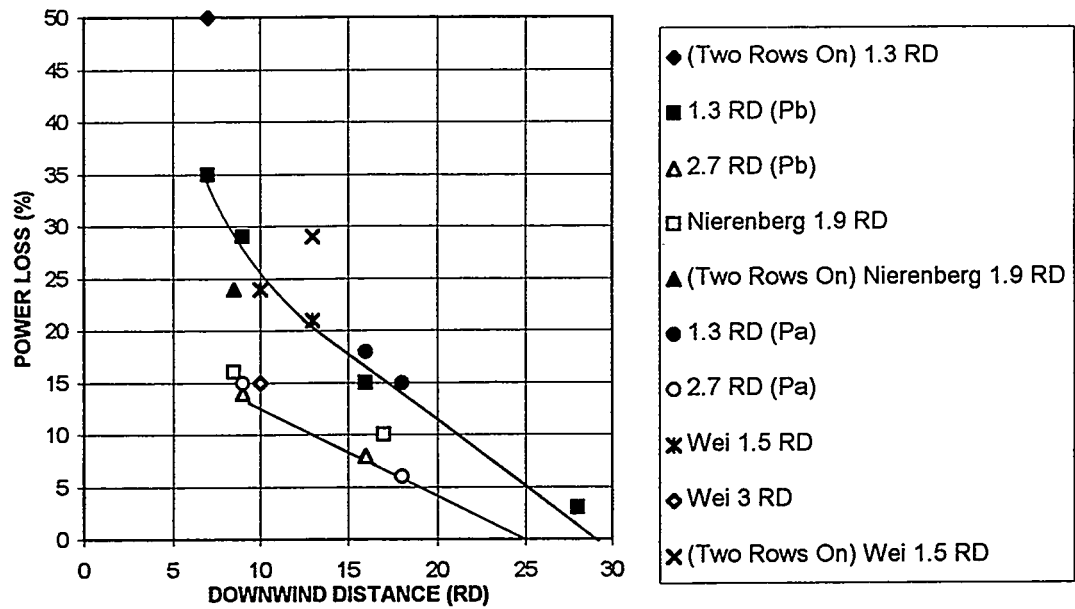


FIGURE 3 WAKE POWER LOSS AS A FUNCTION OF THE AMBIENT TURBULENCE INTENSITY AT SITE Ma FOR WINDS SPEEDS 10.7-11.6 M/S (ALL TURBINES ON)

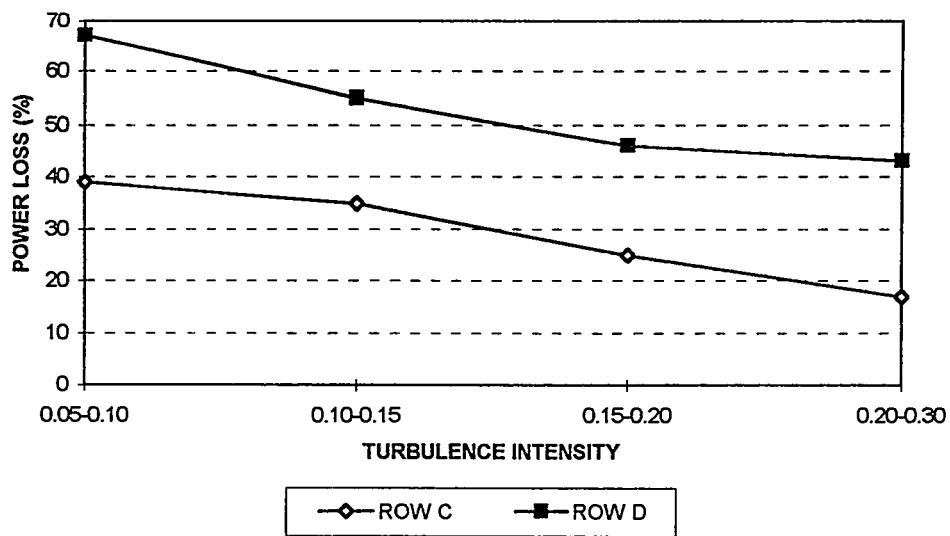


FIGURE 4 WAKE SPEED DEFICITS VERSUS DOWNWIND DISTANCE AND CROSSWIND SPACING (WIND SPEED 10-12 M/S)

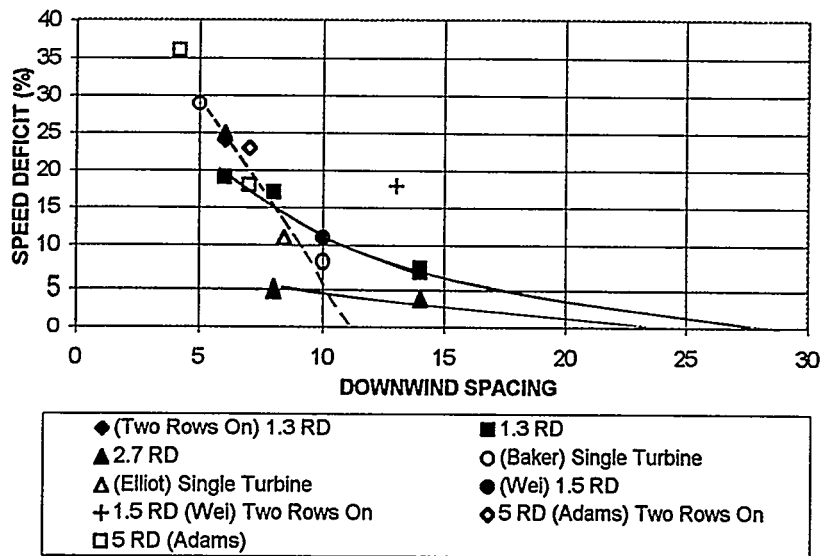


FIGURE 5 INCREASE IN THE TURBULENCE INTENSITY IN THE WAKE AS A FUNCTION OF DOWNWIND DISTANCE (WIND SPEED 10-12 M/S)

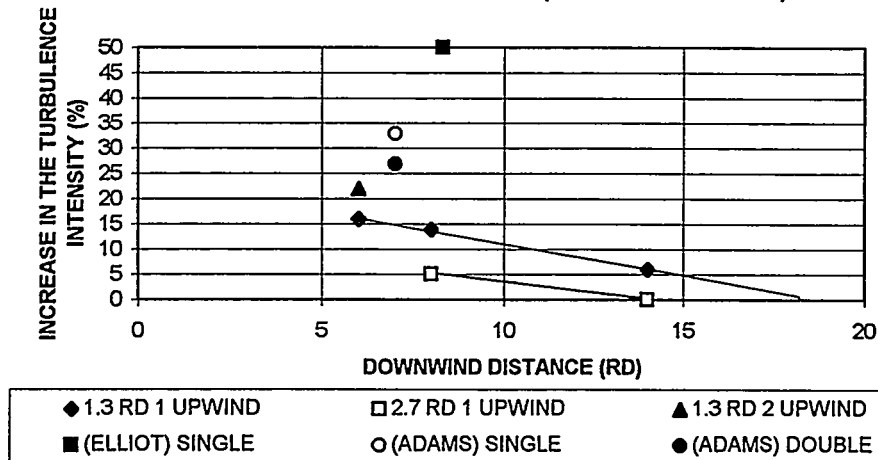
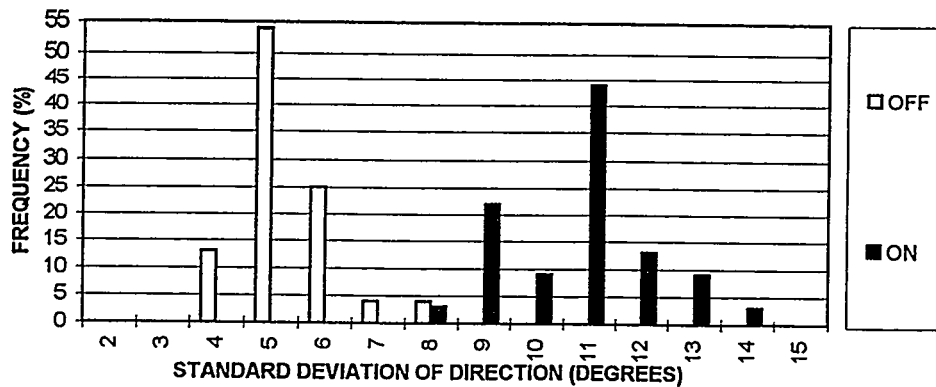


FIGURE 6 FREQUENCY DISTRIBUTION OF THE STANDARD DEVIATION OF WIND DIRECTION AT SITE Md WITH TWO UPWIND ROWS ON AND OFF



WIND SPEED FORECASTING IN THE CENTRAL CALIFORNIA WIND RESOURCE AREA

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ABSTRACT

A wind speed forecasting program is implemented in the summer seasons of 1985 - 87 in the Central California Wind Resource Area (WRA). The forecasting program is designed to use either meteorological observations from the WRA and local upper air observations or upper air observations alone to predict the daily average windspeed at two locations. Forecasts are made each morning at 6AM and are valid for a 24 hour period. Ease of use is a hallmark of the program as the daily forecast can be made using data entered into a programmable HP calculator.

The forecasting program was the first step in a process to examine whether the electrical energy output of an entire wind power generation facility or defined subsections of the same facility could be predicted up to 24 hours in advance. Analysis of the results of the summer season program using standard forecast verification techniques show the program has skill over persistence and climatology.

INTRODUCTION

There is renewed interest in evaluating the possibilities for developing automated processes to forecast hourly estimates of wind energy production from wind energy facilities. Some Department of Energy (DOE) research in wind speed forecasting occurred in the late 1970's and early 1980's when the development of the MOD wind turbines was underway. However, except in Europe, there has been no significant research activity on this topic. The initial wind forecasting studies funded by DOE and performed by Battelle and others used classical approaches. Standard objective forecasting techniques, such as model output statistics (MOS), and semi-objective forecasting techniques, such as man/machine interfaces, were applied in an attempt to see if wind, both speed and direction, could be accurately predicted in areas of known wind speed resources. Examples of this work are presented in Wendell (1978), Gilhousen (1979), Carter and Gilhousen (1980), Wegley (1980), and Notis (1984). Some more recent work in the US was presented by McCarthy (1993, 1996) and Oregon State University (Babour, 1994). Milligan et.al. (1995) authored a study demonstrating that wind speed forecasting and the ability to predict the output of renewable energy facilities would have real economic benefit to a utility.

Research on wind speed forecasting and, correspondingly, the forecast of electric energy output from a wind energy facility is actively pursued in Europe at Riso National Laboratory and at the Rutherford Appleton Laboratory. Scientists have published several recent papers on the application of wind speed forecasting to wind energy facilities (Landberg, 1991, 1994, 1995, 1996; Landberg and Watson, 1992, 1993, 1994). Additional work on this topic has been done by Soder (1994) and Geerts (1984).

Recently, staff at the Institute of Mathematical Modeling (IMM) at the Technical University of Denmark and ELSAM, a Danish utility company, completed a three year study on wind power prediction and dispatch of wind energy facilities within ELSAM's service territory. Wind power facilities may produce nearly 20% of the electrical energy demand in ELSAM's service territory in the next 10 years. IMM and

ELSAM, with the assistance of a grant from the European Union, developed a wind power prediction tool for use in ELSAM's dispatch center (Jensen et.al. 1996). The prediction model provides projections of total wind generated electricity for the ELSAM area for 0.5 to 36 hours ahead in half-hourly time steps. The system uses wind measurements and wind energy facility power measurements to forecast electricity deliveries. Further research is now underway to integrate numerical weather prediction information with energy forecasting models. The European Union (EU) Program "Implementing Short Term Prediction At Utilities", a three year program initiated in January 1996, is designed to develop models to predict wind facility electrical energy output using numerical weather prediction models. Riso National Laboratory in Denmark is the lead agency for this work.

HISTORICAL ACTIVITIES AT KENETECH WINDPOWER

The development of forecasting models at Kenetech Windpower was an outgrowth of the hindcasting activities performed in 1984 and 1985 (McCarthy, 1996). The activities at Kenetech Windpower are summarized in Table 1. Hindcasting was developed to investigate and create long term historical wind speed data bases for selected Altamont Pass sites. The results of the hindcasting work were expanded to develop daily wind speed forecasting models. Initially, forecast models were developed for two sites. Eventually this program was expanded to five sites in Altamont Pass. The logical next step beyond wind speed forecasting was to integrate the forecasted wind speed with the wind plant power curve to predict wind plant energy output. Finally, time series models and climatology were used to evaluate the opportunity to predict short term (1-3 hours in advance) wind speed and wind energy. In addition, it was envisioned expanding the hindcasting approach to the six summer months (April - September) for up to five sites.

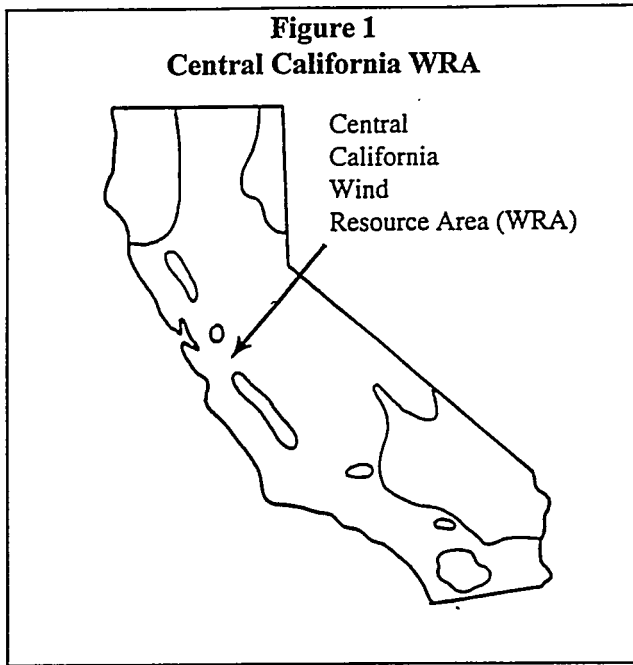
Table 1
Summary of Forecasting and Hindcasting Activities
Kenetech Windpower 1985 - 1988

Year	Activity
1984	Develop Hindcast Model Approach
1985	Select two locations and develop models to predict daily average windspeed Confirm the validity of hindcast modeling techniques at two Altamont Pass sites
1986	Prepare forecasts of daily average wind speed for Summer Season (April to September) Prepare monthly average wind speeds - May, June, and July - at two Altamont Pass sites for a 20-year period - 1965 to 1984 - using hindcast approach.
1987	Prepare forecasts of daily average wind speed for Summer Season (April to September) Develop and test new forecast models for five sites in Altamont Pass
1988	Prepare forecasts of daily average wind speed for Summer Season (April to September) Integrate wind speed forecasts with wind plant power curve to predict energy output (out to 30 hours) Investigate time series analysis techniques for short term prediction of wind speed and energy (1-3 hours)

APPROACH

A model was developed using one season of wind speed data in 1985 and independently tested using two seasons of data, 1986 and 1987. The predictand was the daily average wind speed at two sites in Altamont Pass while the predictors were a series of meteorological variables. The stepwise multiple linear model in the MINITAB Statistical Package is used (1982 release). The approach is similar to that used by the National Center for Environmental Prediction (NCEP) in the development of MOS equations for prediction of weather elements at specific locations.

The wind resource in the Central California WRA exhibits both a seasonal pattern and a diurnal pattern. Higher wind speeds occur in the summer than in the winter and, during the summer, higher wind speeds during the night than during the day. The profile of monthly average wind speeds presented in Figure 2



illustrates the seasonal variability of the wind resource in the Central California WRA. Average wind speeds are highest in the late spring - early summer and lowest during the winter months. The typical diurnal pattern during the summer months is presented in Figure 3. The hourly average wind speeds reach a peak just before midnight and a minimum in the morning around 8 AM PST.

As part of the initial hindcasting study, a large meteorological database was developed. This database was assembled from the Local Climatological Data (LCD) summaries for various observing stations within California, the twice daily Oakland RAOB Sounding, and the Daily Weather Map series. The data for the Oakland RAOB Sounding is available at 0000 Greenwich Mean Time (GMT) and 1200 GMT each day. The selection of these parameters

focused on possible microscale effects, such as the daily temperature differences between coastal locations and selected interior locations and possible synoptic scale influences such as height and height changes at the 700 millibar (mb) pressure level. A multi-year database consisting of 38 meteorological variables was extracted from the hindcasting database. The dependent variables were the calendar day average windspeed (midnight to midnight) and the average wind speed for a twelve hour period from mid afternoon (1500 PST) to early the next morning (0200PST).

LINEAR REGRESSION ANALYSIS

Prior to the initiation of a complex analysis with multiple parameters, extensive simple linear regression analyses consisting of one predictor and one predictand were investigated. No one single parameter was found to correlate well with the daily wind speed or subsets of the daily wind speed in Central California.

Figure 2

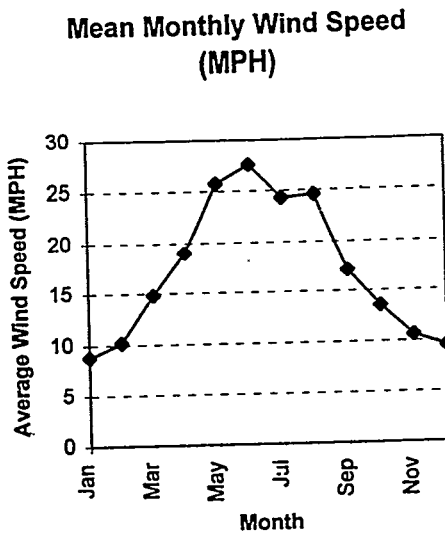
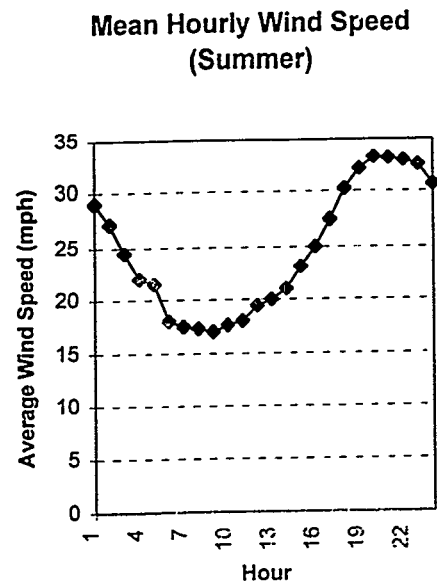


Figure 3



Multiple linear regression was selected as the statistical technique. The statistical model is a linear model in the form:

$$y = m_1x_1 + m_2x_2 + \dots + m_nx_n + b$$

where:

- y is the daily average wind speed at the single reference location;
- $x_1, \dots, x_n$ are meteorological variables serving as predictors;
- $m_1, \dots, m_n$ are numerical coefficients unique to each predictor, and;
- b is a constant value.

The independent predictor values are the 38 meteorological variables which comprise the database. The dependent variables are the average wind speeds for the calendar day or the twelve hour period at the reference site.

The stepwise multiple regression model provides alternative approaches or steps to fitting the independent variables to the dependent variable. Each iteration or step produces a set of predictors, a constant value, the mean square error of the estimate, and the R statistics. The adjusted R^2 value is defined as the percentage of the variance in the dependent variable explained by the independent variables selected in the stepwise procedure.

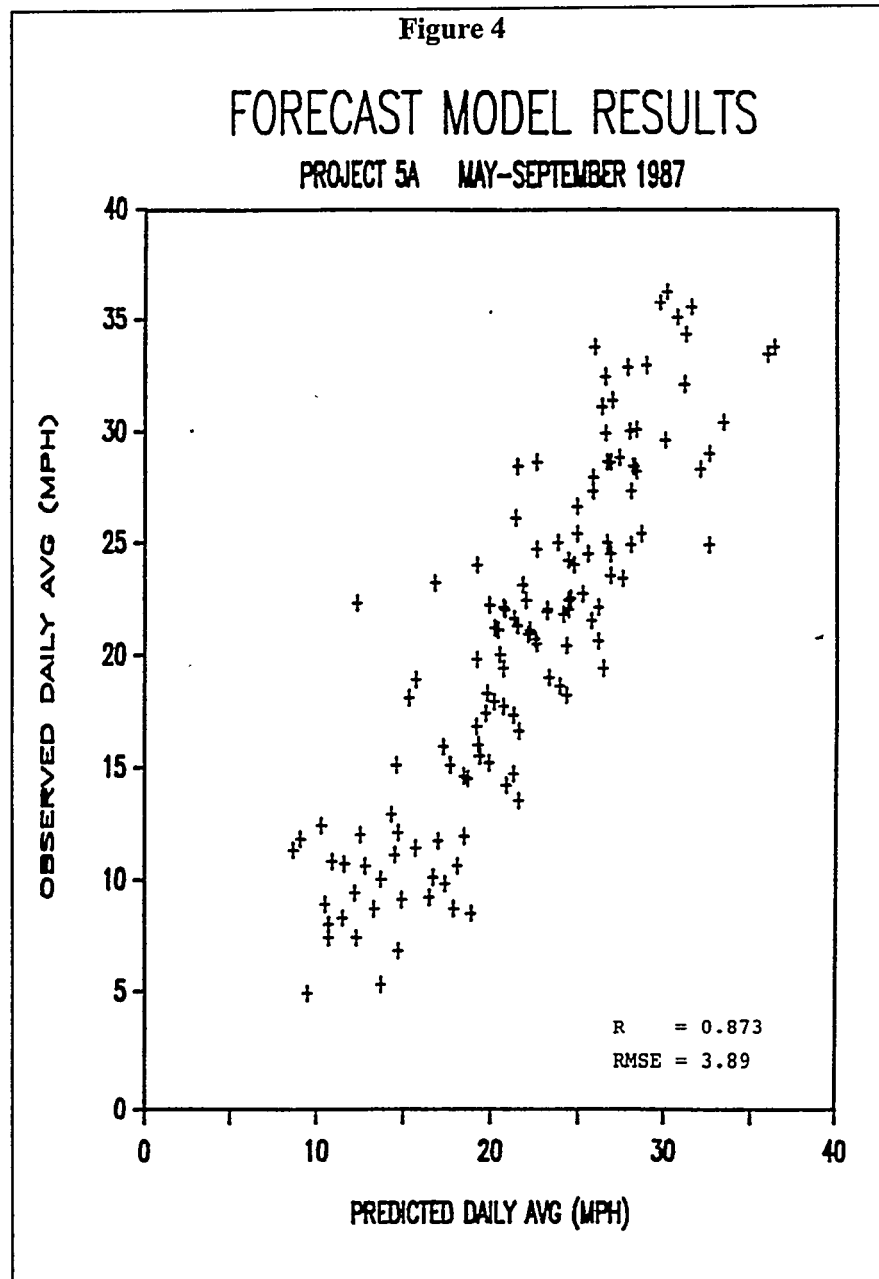
The selection of the best set of independent variables is not based merely on the step with the highest adjusted R^2 value but also consideration of the t-ratio. The t-ratio or t statistic is indicative of whether or not the inclusion of each successive independent variable significantly increases the variance explained by the model. As a general rule, the t-ratio must be greater than 1.96 to include the independent variable in the regression equation. Therefore, the set of predictors with the best adjusted R^2 value and the one having all predictors with t-ratios ≥ 1.96 is the model of choice.

In developing the model, consideration must also be given to seasonality and the investigation of multicollinearity between various independent variables. Seasonality is accommodated using harmonics, the sine and cosine functions, and the use of a sequential number related to the days before and the days after the summer solstice. The linearity of the independent variables is tested both individually against the dependent variables, between the independent variables selected in the stepwise procedure and the dependent variables, and between the residuals.

APPLICATION

Wind speed forecast models to predict daily average wind speed were developed for two sites. The models were programmed into a HP 41CX programmable calculator. Two models were developed for each site, one version of the model assumed that only upper air information was available while the second version of the model assumed that both a local wind speed as well as upper air observations were

available. Each morning at 8:00 AM a forecast was prepared for the current day. Appropriate values were entered into the calculator and the results recorded on a worksheet. These forecasts could be prepared as much as two hours earlier as all necessary data is available by 6AM. As this was considered a testing and evaluation mode, the forecasts for the weekend were prepared on Monday morning. Data used to verify the wind speed predictions were obtained from the observational meteorological towers within the wind plant. One problem with the methodology was the handling of missing data. If one value is missing, the program could not be executed. The lesson is that, for actual forecasting programs, it is essential to have some form of alternatives so a wind speed forecast could be prepared. For example, in 1987 forecasts were prepared for 136 days out of 153 days. Forecasts could not be



prepared on these seventeen days due to incomplete upper air information.

Figure 4 is a scatterplot of the observed versus predicted daily average wind speeds for one of the Altamont Pass Sites in the summer of 1987. The correlation coefficient for this site is 0.873. The correlation coefficient for the second site which was also tested in the summer of 1987 was 0.856

RESULTS AND INSIGHTS

Panofsky and Brier (1968) suggest a number of verification methods for use with forecasting methodologies. One such approach is the contingency table summary to compare forecasted to actual conditions. As a verification technique, the information in a contingency table is often combined into a skill score (S):

$$S = (R - E)/(T - E)$$

where R is the number of correct forecasts, T is the total number of forecasts, and E is the number expected to be correct based on some standard such as chance, persistence, or climatology. To develop the contingency table, the daily average wind speed was segregated into six bins centered on the following average wind speeds (meters per second): 4.2, 6.5, 8.7, 10.9, 13.2, 15.4. The predicted values were compared with the actual values for the summer season of 1986 and 1987. The forecasting skill score was then determined based on the expected number correct associated with chance and the expected number right associated with persistence. Following Panofsky and Brier (1968), a χ^2 Test is used to determine whether the actual score is significantly different from the no-relation score. The application of the χ^2 Test indicates that the hindcasting model exhibits skill in predicting daily average wind speed versus mere chance and also persistence.

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GETTING THERE FROM HERE: EDUCATING THE PUBLIC ABOUT WAYS THAT WIND ENERGY CAN BE PART OF THE SOLUTION TO SUSTAINABLE LIVING

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ABSTRACT:

Today's world faces unprecedented challenges in developing sustainable living styles that are supportable. This paper addresses the issues that relate to identifying problems and educating the public about the solutions to the problems.

INTRODUCTION

Wind energy should be part of the power production used in the world because it keeps the air and water clean, it makes jobs, and it can be done regionally.

Educating the public in these areas is very complex. For several years this has been a puzzle, so to speak, which required a great deal of time, energy and money, all out of pocket, in order to raise awareness and develop a sense of what needed to be done. These are some of the ways that contacts have been made.

VARIETY OF WAYS TRIED IN REACHING PEOPLE

GLOBAL

Internet has allowed for the bulk of the communication, which is one of the great things about it. Large geographic areas particularly can benefit from the ongoing dialogue over information and policy issues. The Alternate Energy listserv is one of the oldest listservs, broad in scope and allowing for global discourse on renewable energy. A newer list, renewable-energy, also allows for policy discussion. Out of these listservs have come many conversations and visits among friends who met on the lists. The potential is great. There are others, but these have a core of experienced folks who talk and do problem-solving on the lists. Other lists are woven into the dialogue; search engines are easy ways to find them by topic or title.

After the global community, there must be efforts made to identify groups at the local, regional, state and national level who are willing to listen to speeches and converse on renewable energy issues.

Missionaries, non-profits, or government agencies working in rural areas can and do promote all sorts of renewable energy sources; funding to install and maintain small wind power projects in rural areas would certainly be worth looking at. Maintenance issues need to be addressed ahead of time so that malfunctioning does not give the technology a bad name. Anything with moving parts needs maintenance; wind turbines are no exception.

Internships around the world are a good way to educate everyone involved about wind power. Margo Guda in Curacao has had interns working with her before and would like to have them again.

Trade schools integrated with mission work would be an ideal place to integrate small wind power manufacture, installation and maintenance into job training in poor countries.

Of course, there are the ubiquitous home pages, too many to count, and many good ones. These are easily searchable with Web browsers so they will not be documented here. A great deal of government-funded information is included here, which is one reason that keeping electronic information access funded at the Federal and state level is so critically important. Having information is only as good as the easy accessibility and proper maintenance of the sites. If a person could only find one way to share information, probably the home page is today's most democratic means of getting information out.

FEDERAL OR STATE GOVERNMENT

Legislation is part of the education process. It educates those promoting wind power, the legislators themselves, and the constituency. While entertaining and exciting, this is also kind of like being on the open ocean; it can be very scary. Legislation truly needs to be participatory, and without a network of educated citizens who swap and update their information regularly and share it with their legislators, it will only become a back room type of activity, leaving out important issues. Good legislation, it seems, should mainly set acceptable boundaries with an understanding of long-term consequences, if that is possible, in order to allow for a great range of practices to be decided regionally. Just as the food industry has regulations about what must be done on food being brought into the state or country, it seems that energy transmission could be regulated in much the same way.

NATIONAL

Obviously, national conferences and other gatherings are ideal meeting places. The drawbacks to national conferences are time, money and energy. Travelling exhibits, media presentations, and teleconferencing can implement tie-ins, aside from listservs and personal contact on phone, letter or email. Books and other publications can also be part of the outreach.

Types of contacts to be made:

Publicity/information people for various organizations

Legislative aides

National groups who have overlapping interests, such as educators, hobbyists, publishers, marketers, investors

STATE OR REGIONAL

Join or start an organization. Once again, email and home pages on the Web are the best and easiest in large geographic areas such as Texas.

Contact publishers and offer to do book reviews for them and get the review published in exchange for a copy of the book.

Solar Energy International is one of several educational sites. Located in Colorado, they also carry their programs around the country and offer certification in specific sustainable living areas to those who take their courses, which includes wind power. All of these and more have the potential of being attractive to missionaries and people working among disadvantaged people around the globe.

Organize tours of research sites, such as Bushland, Alternate Energy Institute, the Energy Center at the University of Texas in El Paso, the public display area owned by Texas Utilities near DFW Airport. Contacts made ahead of time insure that a hospitable welcome will be forthcoming and adequate time given for questions to be answered. These and others are free of charge. EPSEA has met for many years in El Paso, swapping ideas, help and encouragement.

The wind farms near Fort Davis and in the Delaware Mountains are magnificent but much more difficult to tour. Passersby can still get good pictures of them. CSW has a kiosk open to the public next to their solar park; it would be a good model for anyone desiring to set up a public display explaining renewable energy. These should be scattered freely through the school districts.

LOCAL

Civic groups or speaking organizations such as Toastmasters are good venues, although there is no time for followup. The easiest way is to get a copy of the AWEA video, which is a great conversation-starter, and offer to bring it to lunch meetings of civic groups or school organizations. This was a simple step in the right direction, although it was a one-time thing and had very little in the way of follow-up. It is an excellent way of identifying citizens who have the potential of being helpful. Taking business cards to hand out makes contact afterwards easier. This was done for two years in the Abilene area, speaking to groups such as Kiwanis, Abilene Clean and Proud, university classes in environment, management, industrial technology, and political science. Be sure and carry cards with your name and other information if you want to be invited to other places. Matching postcards are a nice, easy asset, too. Friendly professors and civic leader friends certainly open many doors.

Attendance at local events, such as our ArtWalk downtown, is a good place to get better

acquainted with folks who are in decision-making positions.

Church groups were for the most part passive and unresponsive. There is just now a groundswell of real interest among religious groups about environmental issues. This could be good or bad; it will depend on the kind of careful listening and patient explanation about sustainable living issues, and willingness to accept a wide divergence of opinions. There must be some areas of overlap, which can be identified, but it takes constant networking and being non-threatening. Religious groups were formerly the societal hubs that implemented social problems in communities, and the last 30 or 40 years have conditioned people so thoroughly to the concept of governmental solutions to all problems that many folks have never had the opportunity to develop their consciences in these areas.

Habitat for Humanity is one potentially effective interface.

Black churches are generally more responsive to social issues, and this area is just starting to be explored. A speech is scheduled on sustainable living issues for the end of June.

A church in Lubbock, Texas installed wind turbines years ago in order to sell the electricity to the utility, but that did not work out and the wind turbines and others like them in other places are sitting there, unused, because of lack of understanding and cooperation. Utilities, while offering a very valuable service, need to be more open about making the options easily available in terms of cooperating with customers in regard to renewable energy usage. Users also need to be both aware of the problems incurred by integrating renewables, while at the same time being less fearful of the potential. Change is difficult at best, but it can be done with everyone cooperating.

Public schools are probably the best venue for developing interfaces. It is very easy to get invited to speak at public schools, doing short entertaining presentations. Play equipment that looks like parts of a wind turbine, puzzles shaped like the interior parts of a wind turbine, and a small portable working wind turbine would be nice to have. Imagine the fun of having a huge wind turbine blade used as a crawl space or part of a museum or playground exhibit! A nacelle where kids could climb in and use a computer to generate graphics and simulate wind patterns would be a great classroom teaching aid.

Children are eager to live in a caring manner and carry home the information they are given to the supper table. There is a strong need for accurate, unbiased information to be used by teachers who will use it, and they will, showing the values of wind power production.

Old people remember the use of wind for mechanical water pumping as well as for electricity power generation; they should be asked questions and the stories recorded. They will support this process. They would also be an excellent tie-in to school events. Their skills, memories and eager participation are invaluable. Tom Rentz' wind power archives would be a good site to store these stories.

Kites and weather balloons are part of plans for future wind energy presentations; they are fun,

inexpensive, and perfect for demonstrating how to get past the turbulence.

Potlucks advertised in local newspapers or other media will bring families together to form friendships; target audiences would be various local organizations such as Sierra Club, Habitat for Humanity, zoological societies, historical societies, Audubon Society--generally these people are interested in renewable energy as a means of preserving clean air and water. Texas has not had the avian problems that other regions have. Schools, particularly in rural areas, would integrate school and civic events. This is how things are done in small towns.

Museums, zoos and some camps qualify as educational sites in terms of accreditation and funding. These venues should be developed to the hilt because of the wide public accessibility. The public school installation of the 1 MW wind turbine at Spirit Lake, Iowa and the Whisper turbine on the roof of Seaholm High School in Birmingham, Michigan continue to show the general public the value of wind power. Not only this, but the Seaholm High School Universal Sciences program has strong business support regionally, and the students have exceptionally high standardized test scores. The target audience in the minds of everyone who wants public support should be the pregnant lady pushing a stroller with her overalled husband walking next to her. Most folks have no clue where electricity comes from or the issues related to it. In order to promote broad-based support of renewable energy, there must be an understanding of it.

Getting on TV with a solar cooker always draws a crowd; they remember and find the solar cooker wherever it appears. After all, wind folks usually are interested in solar applications too.

The Kern Wind Energy Association has an excellent booklet for use at grade school level. Central and South West Corporation has just produced a short video with accompanying printed materials designed for elementary school use.

The Texas State Energy Conservation Office is in the process of developing a video and other educational materials which will include wind power.

The AWEA video is too advanced for most elementary settings, although it is perfect for high school and up, because so many types of jobs are readily identifiable.

LIBRARIES

Library collections must be developed and librarians educated in wind power issues. Electronic access is not enough. It is invaluable, and a significant part of information availability, but libraries also need to have books, maps, CD-ROMs and other forms of information availability for their patrons to be able to do accurate research. Having one or more libraries in each state with significant amounts of materials doing comprehensive coverage of wind power and related issues will help promote studies in the issues mentioned above. Today's libraries with many types of consortia make information even easier to access, whether locally, electronically or via Interlibrary Loan.

History books by Paul Gipe and Robert Righter are available at reasonable cost and are cataloged

in OCLC. Dr. Gary Johnson's textbook, although somewhat dated, is easy to understand and is on OCLC. These and other books should be added to library collections; they are for high school through adult usage. Of course, there is HOME POWER magazine, which is the sacred text of all small power users, and is a wonderful connecting point for those whose lives revolve around sustainable living as it relates to power production.

ACADEMIC SETTINGS

University programs can weave wind power into a wide range of educational programs, but it will require a broad understanding of the issues involved, as well as adequate funding and library support, without which no decent program or degree plan can occur. Above all, it takes caring and accepting, and a continued sense of helping people work together for solutions. Technical schools would be ideal candidates for developing programs that could promote the wind industry. This will take time, energy and money. It also, in order to become part of the fabric of society, needs to be integrated into academic programs. The University of Texas at El Paso has an Energy Center and a lot of renewable energy research going on. Other states are doing similar things.

Technical schools and academic schools are often at odds; the industrial technology areas of universities can weave together with wind power and computer science, wind power and finance, wind power and management, wind power and insurance, wind power and history, wind power and physics, wind power and environmental overviews, wind power and defense issues, wind power and strength of materials, wind power and publishing of textbooks and reference materials, wind power and urban planning, wind power and geography, wind power and public policy; the list could go on and on. Academics can do serious research on these areas legitimately, but they have to have it shown to them.

NATURAL OUTCOME OF INCREASE AWARENESS AND INVOLVEMENT

Cost alone is not enough of an issue. Safety is not enough. Health issues should be brought up. Cost will fall in line if folks understand the consequences of not choosing renewable energy. A teenager pointed out that not nearly enough emphasis has been placed on the fact that once wind turbines are in place, there is no need to purchase fuel. Other costs only contribute to the jobs created in the research, development, and maintenance of wind turbines and the related infrastructure.

Wind power, alone or as part of a hybrid system, which usually it will be, is one way to stand against what appears to be increasing weather-related global climate change disasters. Research will need to continue in order to see that wind turbines are safe and durable in turbulent weather.

Every wind turbine stands for jobs; this needs to be broken down and pointed out to folks who work in boiler factories, where steel nacelles and towers could be built, in boat shops where fiberglass blades could be fabricated and painted, in laboratories that develop paints and other finishes for use on wind turbines. Wind turbines mean computer jobs, fiberoptic installation jobs,

truck driving jobs, installation and maintenance and management jobs, textbook writing and publishing jobs, jobs training windsmiths. Jobs must be developed in order to offer longterm support. Wind turbines must be safe, effective, manageable means of power production, so that people can take pride in being part of the wind industries' solutions to sustainable living in the future. Parks should be built around wind farms in order to emphasize the clean power production going on. Hybrid systems can be part of museums. Wind farms can be integrated into farming and ranching with little loss of land, an important consideration in states like Texas.

Untapped potential resides in the influential comic strips, movies, comic books, public performances of all kind, and shopping bag advertising, all of which seem like good routes to explore, but should tap into the deep desire for sustainable living, of which clean power production should only be a segment.

CONCLUSION

Wind power can be part of the future of sustainable living because it keeps the air and water clean, it makes jobs, and it can be done regionally in order to promote living that doesn't depend on bringing power sources from the other side of the world.

ICE ACCRETION MODELING FOR WIND TURBINE ROTOR BLADES

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ABSTRACT

The increasing application of wind energy in northern climates implies operation of wind turbines under severe atmospheric icing conditions. Such conditions are well known in the Scandinavian countries, Canada and most of Eastern European countries. An extensive study to develop a procedure for the prediction of ice accretion on wind turbines rotor blades appears to be essential for the safe and economic operation of wind turbines in these cold regions. The objective of the present paper is to develop a computer code capable of simulating the shape and amount of ice which may accumulate on horizontal axis wind turbine blades when operating in icing conditions. The resulting code is capable to predict and simulate the formation of ice in rime and glaze conditions, calculate the flow field and particle trajectories and to perform thermodynamic analysis. It also gives the possibility of studying the effect of different parameters that influence ice formation such as temperature, liquid water content, droplet diameter and accretion time. The analysis has been conducted on different typical airfoils as well as on NASA/DOE Mod-0 wind turbine. Results showed that ice accretion on wind turbines may reduce the power output by more than 20%.

1 INTRODUCTION

Over the years, a considerable engineering research and development (R & D) of wind machines with emphasis on the aerodynamics, structural, and system characteristics have been made to maximize energy capture and convert wind energy to electric power. Today, R & D efforts on renewable wind energy are continuing to promote the development and use of advanced and accurate wind energy systems which are economically competitive and emission-free. In Canada, the more promising geographical regions for wind energy development are concentrated primarily in isolated communities located in Arctic, sub-Arctic, and coastal areas where temperatures are very cold. However, while these cold regions represent the most significant market potential of wind turbines, a few attempts have been made to investigate and analyse the phenomena of atmospheric icing and its negative effects on the performance and efficiency of wind turbines.

In recent years, different studies have been conducted to investigate the problem of icing on wind turbine blades. In Finland, VTT Energy [1, 2] is investigating arctic wind technology development, particularly using deicing solutions. They are also developing a numerical code to analyze rime ice accretion on blades, "TURBICE". In Germany [3], the Deutsches Windenergie Institute, with several European countries are investigating the effects of ice accretion on rotor blade, in particular, blade loads and structure, control systems and rotor dynamic behavior. In United-States, the Department of Aeronautical and Astronautical Engineering of University of Illinois at Urbana-

Champaign [4], after studying for many years ice accretion on aircraft, has recently started to analyze the performance of wind turbine under icing conditions. In Canada different research centers studied wind turbines in cold regions. Kolomeychuk and Sillis [5] have examined potential icing effects on wind turbines, Bose [6] experimented a small HAWT in icing conditions in Newfoundland, and David Craig and Douglas Craig [7] studied a 150 kW wind turbine on Haeckel Hill in Yukon to determine its performance in harsh conditions. In Montréal, at the J.A. Bombardier Chair of École Polytechnique de Montréal, numerical codes to predict ice accretion on HAWT blades and aircraft wings have been developed in recent years [8, 9, 10]. Currently, an extensive work is performed to simulate de-icing system to remove ice from wind turbine blades. This project is also supported by "Ministère de l'Énergie et des Ressources du Québec". In the present work results using the icing code for the prediction of ice shapes and performance degradation of an HAWT are presented.

2 MATHEMATICAL MODEL

The methodology used to compute ice accretion on the blade is similar to the prediction of ice accretion on aircraft wings. The model is based on *CANICE* ice prediction code developed for in-flight aircraft icing [10]. *CANICE* is an engineering analysis tool for the prediction of ice accretion characteristics and ice shapes over single airfoils, multi-element airfoils and wings. *CANICE* can be used to compute ice catch rates for anti-icing system requirements as well as a basis for the prediction of ice shapes used during aircraft certification. This code has been used and validated by Canadair against experimental data collected during tests conducted at NASA Lewis Icing Tunnel Test Facility. In order to study the effects of ice accretion on wind turbines, this code has been modified to handle ice prediction on HAWT rotor blades. The mathematical model includes *i*) Aerodynamic model, *ii*) Droplet trajectory calculation, *iii*) Thermodynamic analysis, *iiii*) Ice shapes update, *v*) Performance degradation. The Icing simulation is based on the calculation of the impingement particles on the selected blade radial location which involves the calculation of the droplet trajectories, by integrating the equation of motion and the computation of the local flow field using a panel method. The computation is an iterative process with a time- stepping procedure where successive thin ice layers are formed on the surface and followed by flow field and droplet impingement recalculations. Performance degradation are calculated using two semi-empirical models to estimate lift and drag coefficients.

2.1 Flowfield calculation

To obtain the angle of attack as a function of radial location along the blade for nonice conditions, the code uses the blade element theory where the rotor is divided into a number of spanwise elements at radial stations along the blade [11]. The axial and tangential velocity interference, a and a' , are computed using an iterative process by equating the force on each blade element with the change in the air momentum flowing through the annular strip as shown in Figure 1. The relative velocity and angle of attack are given by [12]

$$W^2 = V^2 \left[A^2 \cos^2 \psi + B^2 X^2 (r/R)^2 \right] \quad (1)$$

$$\alpha = \phi - \beta_t \quad (2)$$

where the coefficients $A = 1 - a$ and $B = 1 - a'$, the tip speed ratio $X = \omega R \cos \psi / V$, β_t is the twist angle, ψ the coning angle, ω is the turbine rotational speed, and the angle of the incoming

flow to the plane of rotation, ϕ , is given by

$$\phi = \arctg\left(\frac{R}{r}\right) \left(\frac{1-a}{1+a'}\right) \left(\frac{\cos\psi}{X}\right) \quad (3)$$

By selecting the atmospheric icing conditions, the local velocity and angle of attack as a function of radial stations are used in the icing simulation to predict ice shapes on each blade section.

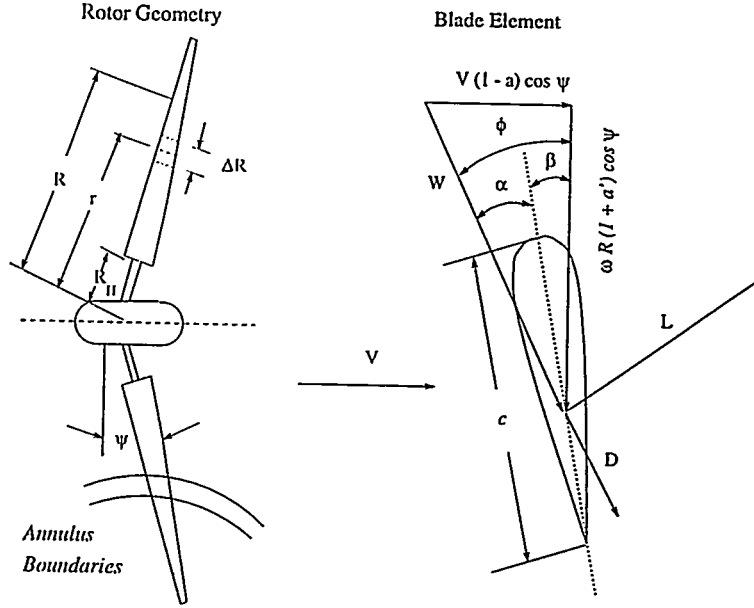


Figure 1: Rotor geometry, flow velocities and forces on a blade element

2.2 Droplet Trajectory Calculation

Droplet trajectories are determined by solving the equation of motion to obtain the entire path for each droplet. At each integration step, the local velocity needed to solve the droplet equation of motion is obtained from the flowfield solution using Hess & Smith panel method [13] while the integration is continued following droplets until they impinge on the airfoil surface or pass downstream of the airfoil. The forces acting on a moving droplet are: the aerodynamic drag force $\vec{F}_D$, the buoyancy force $\vec{F}_b$ and the gravitational force $\vec{F}_g$

$$m \frac{d^2 \vec{r}}{dt^2} = \vec{F}_D + \vec{F}_g + \vec{F}_b \quad (4)$$

The droplet equation of motion can be written as

$$\frac{d^2 \vec{r}}{dt^2} + \frac{C_D Re}{24} \frac{1}{K_A} \frac{d\vec{r}}{dt} = \vec{K}_G + \frac{C_D Re}{24} \frac{1}{K_A} \vec{V}_a \quad (5)$$

where $\vec{K}_G = (\rho_d - \rho_a)\vec{g}/\rho_d$, $K_A = \rho_d D^2/(18\mu_a)$ and droplet Reynolds number $Re = \rho_a D V_r/\mu_a$. m is the mass of the droplet ρ_a and ρ_d the densities of air and water, $\vec{V}_a$ the air velocity vector and $\vec{r}$ the droplet position. The coefficient $C_D Re/24$ in Eq. 5 is a function of Reynolds number and

can be determined using a steady-state drag coefficient for a sphere [14]. The droplet equation of motion represents a second order differential equation which can be solved using classical difference methods. Once the droplet trajectories are known, the global collection efficiency E_m , which represents the ratio between the area where droplets impinge on the airfoil and the total frontal area, is derived by means of limit trajectories on the body upper and lower surfaces while the local collection efficiency is given by $\beta = dy/ds$. These coefficients are useful for the determination of the mass flux of water impinging on the wing surface.

2.3 Thermodynamic Analysis

Thermodynamic characteristics of the freezing process of the incoming liquid water striking an iced blade is presented by considering the mass and energy balance on each airfoil blade section. This will allow us to calculate glaze ice formations which occur when only a fraction of the water droplets freezes upon impact while the remainder runs back along the surface or along existing ice and freezes downstream. The thermodynamic analysis is based on the first law of thermodynamics which states that the mass and energy must be balanced in a control volume on the surface [10]. Based on the heat balance and the mass flux, the fraction of the freezing water droplets on each control volume can be determined. The mass balance will take into account the mass of water coming from the panels upstream, the mass of water running to the panels downstream, the mass of water that evaporates, the mass of water that freezes on impact and the mass of ice that leaves by sublimation when the surface is dry or by evaporation when the surface is wet.

$$\dot{m}_{im} + \dot{m}_{in} = \dot{m}_{va} + \dot{m}_{ou} + \dot{m}_{so} \quad (6)$$

The energy balance will take into account the convective heat losses, latent heat gain, heat loss due to evaporation and sublimation and the heat gain due to kinetic energy. The model developed is based on work by Messinger [15]. The enthalpy and internal energy are calculated in relation to a given reference state and depend on the type of surface involved. The energy balance for a control volume is given by [10]

$$\dot{E}_{so} + \dot{H}_{va} + \dot{H}_{ou} - \dot{H}_{in} - \dot{H}_{im} = \dot{Q}_f - \dot{Q}_c \quad (7)$$

The convective heat transfer coefficient, h_c , used is based on empirical relation using Reynolds analogy, one for the laminar region, depending on thermal conductivity of air, surface velocity and roughness, and one for turbulent region, depending on the local skin friction coefficient, roughness Stanton number, Prandtl number and sand grain roughness.

Finally, the node position is displaced by the average of the ice thicknesses of the neighbouring panels on the normal to the surface ($\delta_{Ni} = (\delta_{i-1} + \delta_i)/2$).

2.4 PERFORMANCE DEGRADATION

To determine the resulting performance degradation due ice accretion on wind turbine blades, the two semi-empirical models that have been studied are those given by Gray and Bragg [16, 17] which give correlations for the increasing drag coefficient for rime and glaze ice. The new drag coefficient for an iced section blade is given by:

$$C_{Dice} = (1 + \Delta C_D/C_D)C_D \quad (8)$$

where ΔC_D is calculated by one of the two empirical models. Presently, more work is undertaken to compute performance using these correlations.

3 RESULTS AND DISCUSSIONS

The amount and shape of ice collected on wind turbine blade surface depend on a number of meteorological and aerodynamic conditions including liquid water content (LWC), droplet size, temperature, airspeed, and time accretion. In the present study results of ice shapes on turbine blades given by *CANICE-WT* (icing for wind turbines) have compared to *TURBICE* prediction as furnished by Mauri Marjiemi [18] from VTT. The analysis has been performed on a NACA 63-213 and NACA 63-218 [8] airfoils with the following conditions: angle of attack 2, 3, 6, 9 and 11 *deg.*, freestream velocity 36.2, 37.1, 50.6, 51.2, and 52.4 *m/s*, ambient temperature -6. °C, liquid water content 0.2 *kg/m³*, accretion time 1 h, and airfoil chord 0.6 *m*.

Figure 2 shows the overall flowchart for the icing analysis on wind turbine rotor blades. The resulting typical droplet trajectories calculation around a NACA 23018 airfoil are given by Figure 3. In order to compute the ice shapes on a wind turbine blade the code has been applied on the NASA/DOE Mod-0 HAWT. Results of ice shapes and local collection efficiency for different blade sections at temperatures of -18 °C is given by Figure 4. Result of the mass distribution and freezing fraction along the blade at different temperature is given by Figure 5. We observe that the mass of ice accumulated on the blade increases when the temperature decreases. This shows the transition between the rime ice and glaze ice conditions. When the freezing fraction f approaches 1, then the ice is mostly in rime conditions while at temperature of -2 °C the ice is in glaze conditions where the ice shape looks like double horned. Finally to estimate the performance degradation of the presence of ice on the wind turbine we have used two semi-empirical models for lift and drag conditions as given by Gray and Bragg [16, 17]. Both models, as shown by Figure 6, give comparable results. Compared to the performance of a clean wind turbine blade, the performance degradation of an iced wind turbine blade may decrease up to 20%.

4 CONCLUSION

An ice prediction code has been developed for the analysis of ice accretion characteristics on wind turbine blades. The original icing code has already been applied and validated for in-flight aircraft icing. Then, it has been adapted and coupled with aerodynamic module for HAWT ice prediction. Some results have been compared to *TURBICE*. Both codes gave similar results with respect to limit impingement, shape and mass of accreted ice. The present code has the possibility to include thermodynamic analysis as well as the effects of supercooled large droplets. The degradation of wind turbine performance in icing conditions has been found to be more than 20 %. Currently more work is undertaken to validate these results with available experimental data and simulate the de-icing system used to remove ice from rotor blades.

ACKNOWLEDGEMENTS

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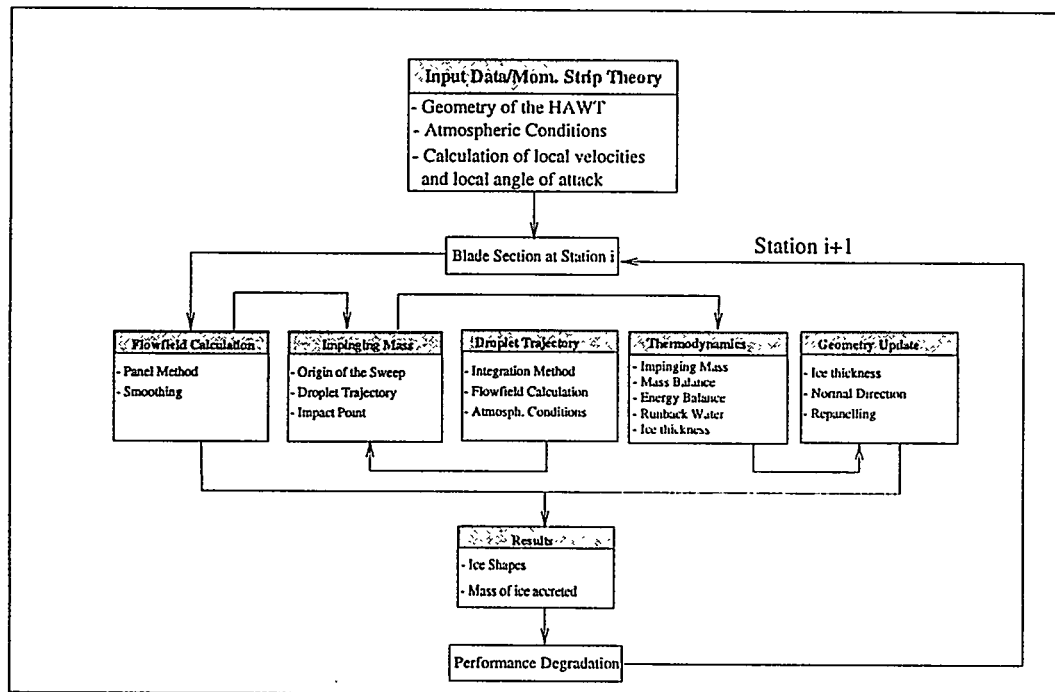


Figure 2: Flowchart of ice accretion prediction on wind turbine blades

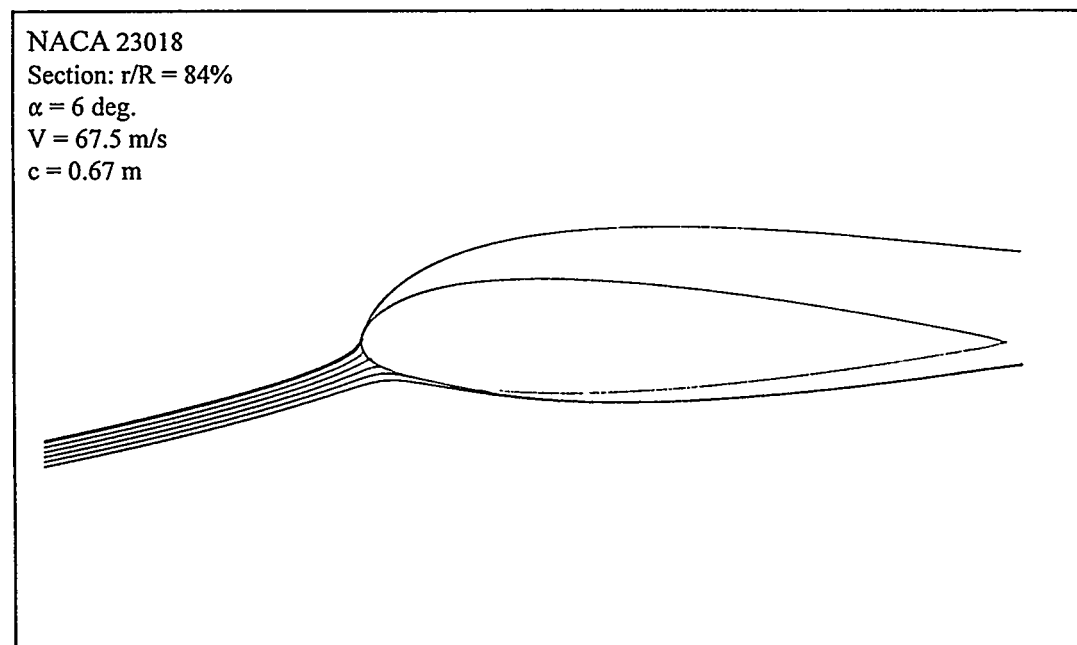


Figure 3: Droplet trajectories around a NACA 23018 airfoil

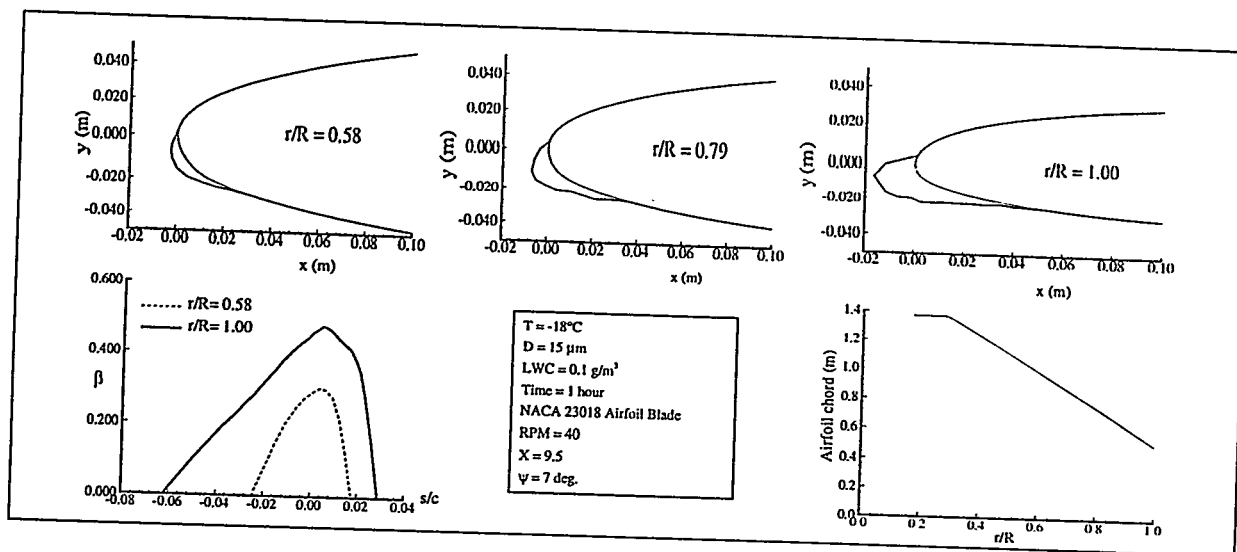


Figure 4: Ice shapes and local collection efficiency at different blade sections

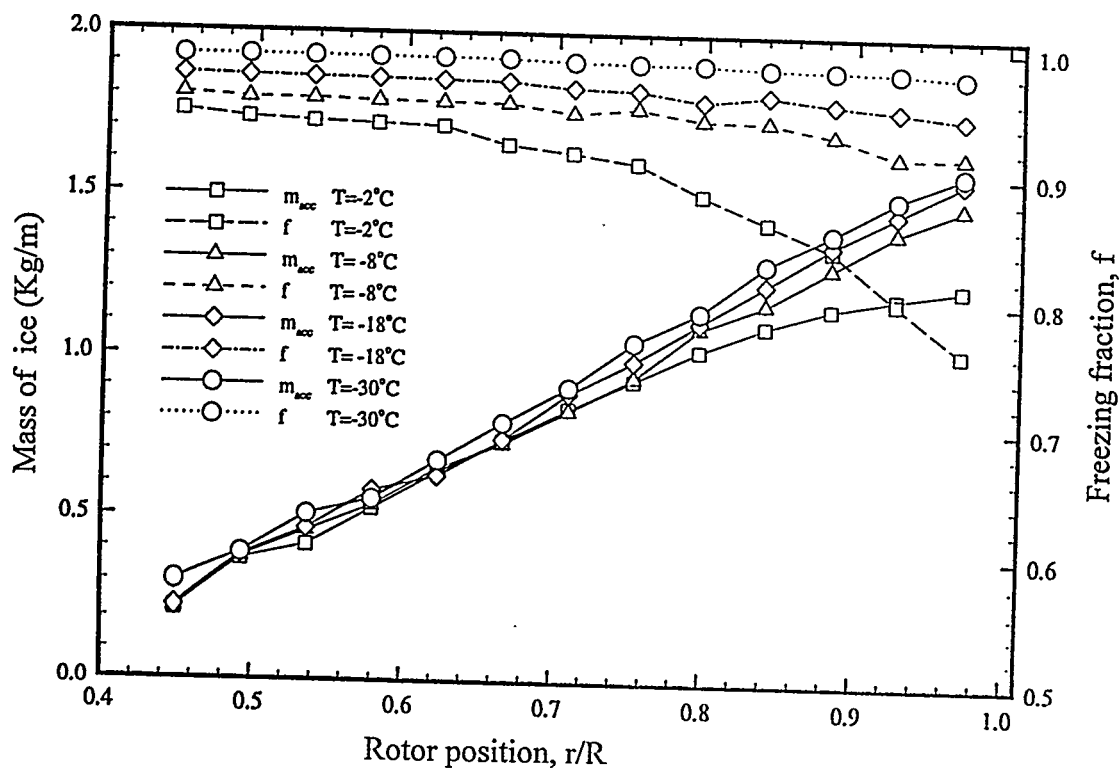


Figure 5: Distribution of ice mass and freezing fraction along the blade sections

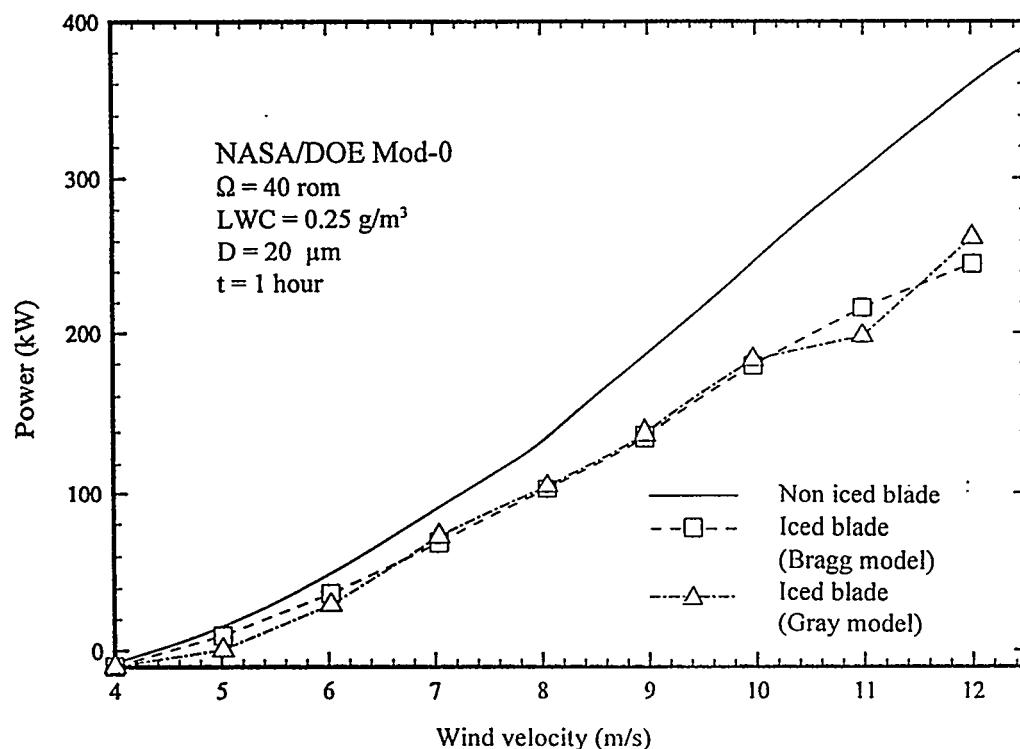


Figure 6: Performance degradation due to ice accumulation at temperature -18°C

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DEVELOPMENT OF PASSIVE-CONTROLLED HUB (TEETERED BRAKE & DAMPER MECHANISM) OF HORIZONTAL AXIS WIND TURBINE

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ABSTRACT

For the purpose of the improvement of reliability of the Mega-Watt wind turbine, this paper indicates the development of an original mechanism for the passive-controlled hub, which has the effects of braking and damping on aerodynamic forces. This mechanism is useful for variable speed control of the large wind turbine. The passive-controlled hub is the combination of two mechanisms. One is the passive-teetered and damping mechanism, and the other is the passive-variable-pitch mechanism. These mechanism are carried out by the combination of the teetering and feathering motions. When the wind speed exceeds the rated wind speed, the blade is passively teetered in a downwind direction and, simultaneously, a feathering mechanism, which is linked to the teetering mechanism through a connecting rods, is activated. Testing of the model horizontal axis wind turbine in a wind tunnel showed that the passive-controlled hub mechanism can suppress the over-rotational speed of the rotor. By the application of the passive-controlled hub mechanism, the maximum rotor speed is reduced to about 60%.

INTRODUCTION

Recently, much progress has been made in the development of large wind turbines to produce electricity. Wind turbines with 1MW output and a 60m diameter are being developed for the commercial market. One important aspect of these turbines is variable speed control. For the fluctuating wind or the wind shear, a teetered hub is useful for the control of large wind turbine.

This paper describes development of a new device for variable speed control, a passive teetered brake & damper mechanism whose purpose is output control of 1MW-class wind turbines, and the experimental testing of its performance with a model wind turbine in a wind tunnel. This new mechanism can make blades incline to downwind and also change the pitch by means of aerodynamic force acting on the blade. With the use of this mechanism, the output power is passively suppressed in the range over the rated power, which means over-rotation is reduced, due to acting by two kinds of blade motions of the teetering and feathering. This passive-controlled hub mechanism has a damping effect on fluctuating force acting on the blade caused by gusts and the velocity difference between upper and lower areas in a rotating plane made by an atmospheric boundary layer.

NOMENCLATURE

C_P	: power coefficient = $P/0.5 \rho U^3 \pi R^2$
C_Q	: torque coefficient = $Q/0.5 \rho U^3 \pi R^2$
N	: rotational speed of the rotor [rpm]
P	: output power [W]
R	: rotor radius = 0.7 m
Q	: shaft torque [N·m]
U	: wind speed [m/s]
γ	: feathering angle [deg]

- ζ : teetered angle [deg]
 θ : initial setting pitch angle [deg]
 λ : tip speed ratio

EXPERIMENTAL APPARATUS AND METHODS

Figure 1 shows the schematic outline of the experimental equipment. The experiment is carried out in an open-jet wind tunnel with an outlet diameter of 1.6m using a maximum wind speed of 15m/s. The test wind turbine has three blades and a diameter of 1.4m. The rotating plane is set at $1d$ (d : wind turbine diameter) downwind from the wind tunnel outlet. The brake & damper mechanism is mounted in the boss. It is equipped with a torque meter, a variable speed generator, a potentiometer for measuring azimuth angle, and a rotational speed sensor. A potentiometer for measuring the teetered angle is set in the hub. The wind velocity is changed in the range of 8 - 12m/s in this experiment. The rated wind speed of this wind turbine is about 11m/s. Therefore, the operational performance of the passive mechanism is investigated in wind speeds ranging from 10m/s to 12m/s in this paper. The rotor speed is manually controlled in the range from 300 rpm to 950 rpm by the variable speed induction generator with a inverter generation system. Table 1 shows the specifications for test blade which is the twisted tapered.

TABLE 1 CONFIGURATION OF TEST BLADE

	Twisted and tapered blade
Airfoil section	NACA4415
Tip chord length	143 mm
Root chord length	113 mm
Radius of rotor blade	700 mm
Twist angle	20 degree
Aspect ratio	4.167

Figures 2 and 3 show the schematic outlines of the passive teetered brake & damper mechanism. This mechanism consists of the blade holder on the teetering axis, the feathering lever connected to the blade axis, the rod end, the spring and damper. In Fig.3 (b), the motion of the blade tip is shown. The motion of the root of the blade holder is restricted by the spring and damper. When aerodynamic force acts on the blade and the thrust force overcomes the spring force on the root, the blade inclines in the downwind direction, which is teetering motion. The blade axis, which is supported by the blade holder, can be rotated by the feathering lever and the rod end, that is, the feathering motion is controlled by the link mechanism. As a result, the teetering motion links the feathering motion around the blade axis. In this paper, the feathering motion means the variable pitch motion. The feathering angle is changed in the direction of increasing the angle of attack, which means the negative pitch direction. Each blade is controlled independently by the brake & damper mechanism.

In the following discussion, a wind turbine rotor with the passive teetered brake & damper mechanism is called simply a passive control rotor. A wind turbine rotor whose blades are fixed to a hub is called a fixed rotor. The relationships between the teetered angle and the feathering angle is shown in Fig. 4. The teetered angle is initially set at 0 degrees at the stationary state and it can be moved to the maximum angle of 6 degrees in operation. The feathering angle is initially set at 0 degrees at the stationary state and it can be moved to the maximum angle of 12 degrees. The teetering motion caused by the aerodynamic force is controlled by a combination of the coil spring and damper. The rate of the feathering angle γ to the teetered angle ζ can be set at 1.0 and 2.0 in this equipment. In this paper, the results of the $\zeta : \gamma = 1:1$ is shown.

The relationship between C_P and λ depends on the initial setting pitch angle. However, as the results from the experiments shown in Fig.11, the initial setting pitch angle, where the maximum of C_{Pmax} is obtained, is 0 degree. Thus the experimental results at 0 degree are used in the following discussion.

EXPERIMENTAL RESULTS AND DISCUSSION

Effects of Teetering Motion on Rotor Performance

Figure 5 shows the relationship of the power coefficient C_P against the tip speed ratio λ for the case of the teetering motion of the blade. In this case, the feathering angle is fixed. The initial pitch angle θ was set at 0 degree. The wind speed were fixed at 10 and 12 m/s. The effects of the wind velocity on C_P - λ curve can not be seen from the figure. For both wind speed cases, C_P is increasing with the tip speed ratio up to $\lambda=3.5$. C_P is rapidly changed in the range of $2.5<\lambda<3.0$. The maximum value of C_P is 0.39 at the tip speed ratio of $\lambda=3.5$. C_P takes large value in the range of $3.0<\lambda<4.0$, and then, C_P is rapidly decreasing over the range of tip speed ratio of $\lambda=4$.

Figure 6 shows the relationship of the shaft torque coefficient C_Q against the tip speed ratio λ for the same condition obtained in Fig.5. C_Q is rapidly changed just below $\lambda=3.0$, which is similar tendency to C_P - λ curve in Fig.5. However, C_P is rapidly decreasing with the tip speed ratio in the range over $\lambda=3.0$, that is, the peak of C_Q - λ curve is sharp at $\lambda=3.0$.

Effects of Feathering Motion on Rotor Performance

Figure 7 shows the relationship of the power coefficient C_P against the tip speed ratio λ for the case of the feathering motion of the blade. In this case, the teetered angle is fixed. The initial pitch angle θ was set at 0 degree. The effects of the wind velocity on C_P - λ curve can be slightly seen in the range of $\lambda>3.0$ from the figure. For both wind speed cases, C_P is increasing with the tip speed ratio up to $\lambda=3.5$. The maximum value of C_P is 0.40, which is almost the same value for the blade with teetering motion shown in Fig.5. However, compared to the operation with the teetering motion, the tip speed range where large C_P value is obtained becomes small, that is, C_P is rapidly decreasing just over the range of tip speed ratio of $\lambda=3.5$.

Figure 8 shows the relationship of the shaft torque coefficient C_Q against the tip speed ratio λ for the same condition in Fig.7. Compared to the C_Q curve for the operation with the teetering motion shown in Fig.6, C_Q is gradually increasing with the tip speed ratio up to $\lambda=3.5$. The maximum value of C_Q is 0.13, which is almost the same value as that for the teetering motion.

Passive Control due to Combination of Teetering and Feathering Motions

Figure 9 shows the results of four kinds of power coefficient curves using different controls. The symbols in the figure show refer to the fixed rotor, the teeter-control only (shown in Figs.5 and 6), the feather-control only (shown in Figs.7 and 8) and the passive control due to combination of teeter and feather controls. In figure the pitch angle is set at 0 degree and the wind speed is fixed at 12 m/s.

From the figure, the feather control is more useful for the suppression of the power in the high tip speed range than the teeter control in this experimental condition.

Comparisons at each control at a certain tip speed ratio of the rotor show some differences over the tip speed ratio of $\lambda=3.5$ where the maximum C_P is obtained. In the operational condition where λ is higher than that of C_{Pmax} , C_P of the teeter-only or the feather-only control is lower than that of the fixed rotor, but higher than that of the passive control with a combination of the teeter and feather control. Therefore, combination of teeter and feather controls is more useful for suppression of C_P than that with

individual control of teeter or feather control.

The maximum power coefficient reaches $C_P=0.41$ for the fixed pitch angle operation at the tip speed ratio $\lambda=3.5$. The performance curve for the passive control almost agrees with the fixed pitch one up to the tip speed ratio of $\lambda=3.5$. Compared with the curve of the fixed rotor, C_P for the passive control rapidly drops over tip speed ratio 3.5.

Figure 10 shows the relationship between the teetered and feathering angles with the same experimental condition of Fig. 9. The initial teetered angle at the stationary state is held at 0 degrees up to tip speed ratio $\lambda=2.7$ since the spring force of the passive-controlled hub mechanism exceeds the aerodynamic force. Then, the teetered angle gradually increases over $\lambda=2.7$. It can be seen that the passive-controlled hub works over $\lambda=2.7$ automatically. Owing to the balance of the aerodynamic, spring and centrifugal forces, the teetered angle is changed over $\lambda=2.7$. According to the teetering motion, the feathering angle increases over $\lambda=2.7$, and reaches 4.5 degrees at $\lambda=5.0$.

Suppression of Maximum Rotor Speed due to Passive Control

Figure 11 shows the comparison of the maximum rotor speed due to the passive control rotor and fixed blade rotor. The initial setting pitch angles are selected as -2, 0, 2 and 4 degree in this figure. It can be seen that the maximum rotor speed is largely suppressed by the passive control. The difference of the maximum rotor speed by the passive control rotor and fixed blade rotor is increasing with the wind velocity. The rotor speed is the most suppressed by the passive control with the initial setting pitch angle of 0 degree in all the setting pitch angles. It seems that the passive control is useful for the braking of the rotor speed in the high wind speed range.

CONCLUSIONS

- (1) The passive teetered brake & damper mechanism is useful for suppression of the output power in the range over the rated wind speed due to combination of teetering and feathering motions.
- (2) The passive teetered brake & damper mechanism can suppress the over-rotational speed passively in the range over the rated wind speed.

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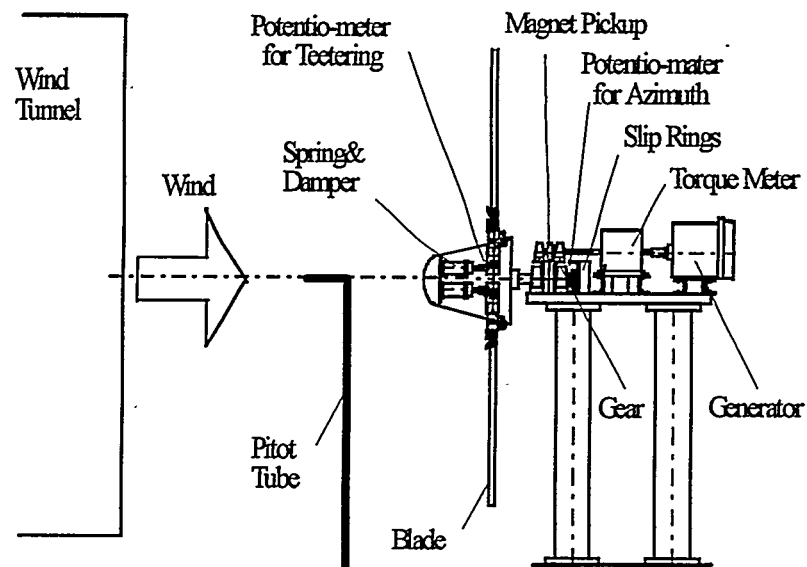


FIGURE 1 EXPERIMENTAL APPARATUS

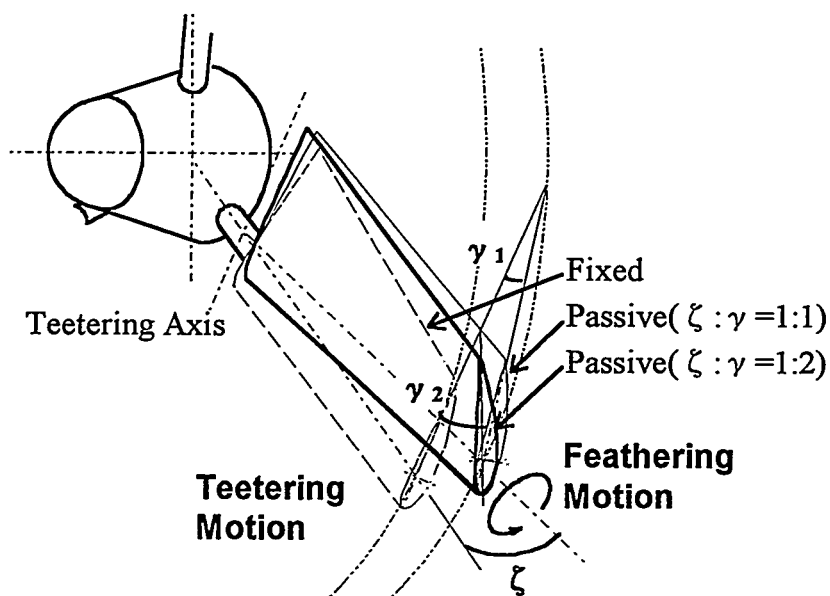


FIGURE 2 OVERVIEW OF TEETERED BRAKE & DAMPER MECHANISM

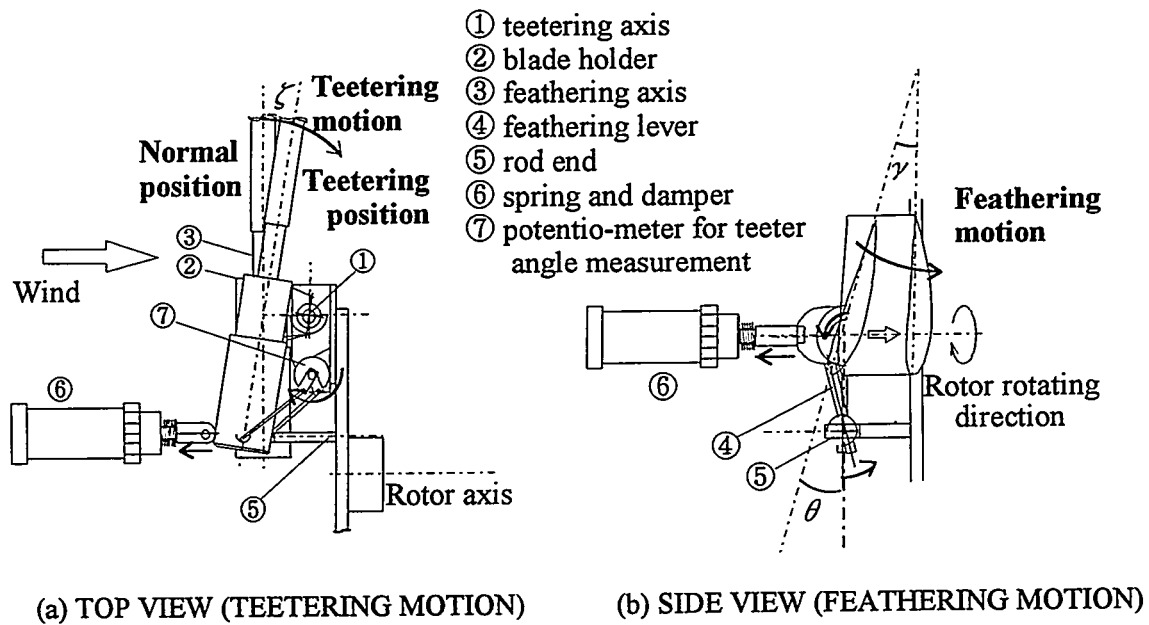


FIGURE 3 PRINCIPLE OF TEETERING AND FEATHERING MOTIONS OF TEETERED BRAKE & DAMPER MECHANISM

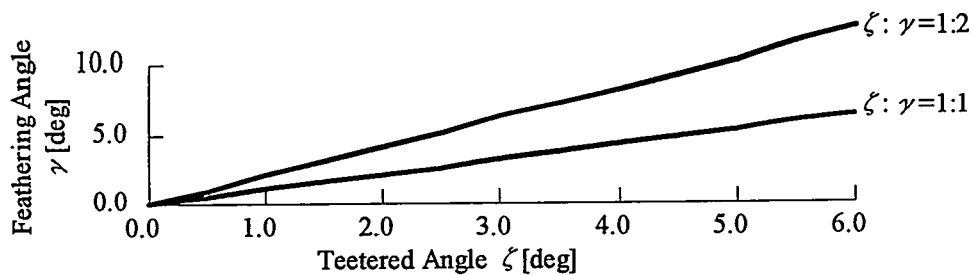


FIGURE 4 RELATIONSHIP BETWEEN TEETERED ANGLE ζ AND FEATHERING ANGLE γ (INITIAL SETTING PITCH ANGLE $\theta = 0$ [DEG])

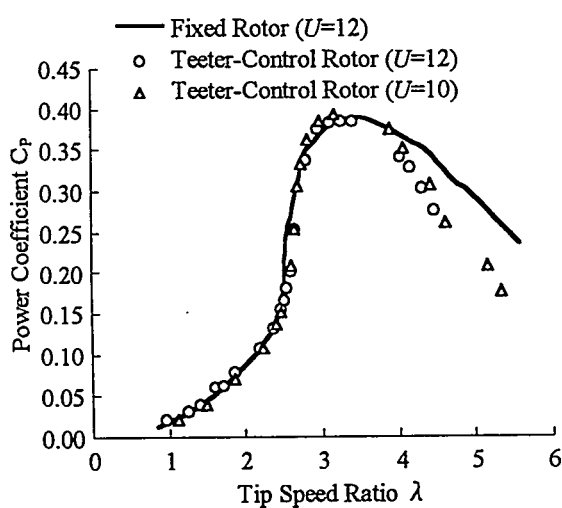


FIGURE 5 POWER COEFFICIENT CURVE OF ROTOR WITH TEETERING MOTION

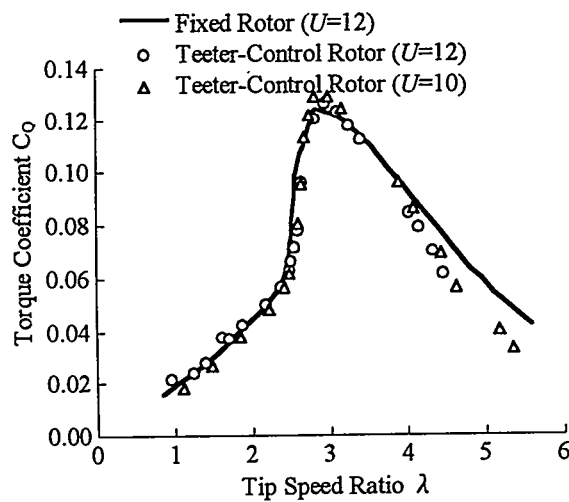


FIGURE 6 TORQUE COEFFICIENT CURVE OF ROTOR WITH TEETERING MOTION

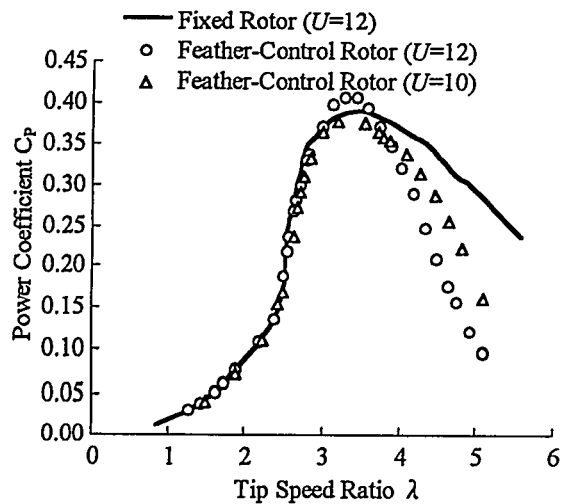


FIGURE 7 POWER COEFFICIENT CURVE OF ROTOR WITH FEATHERING MOTION

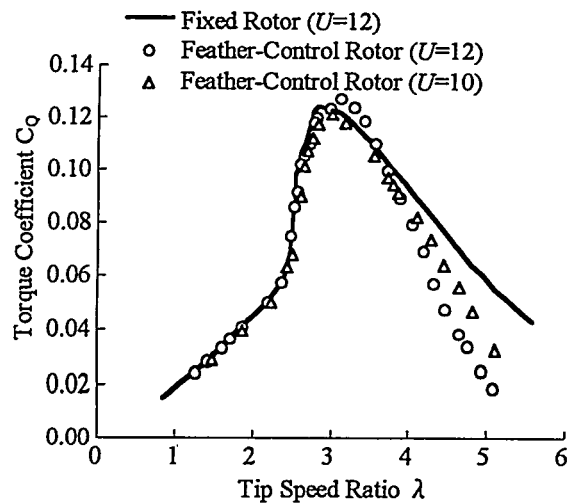


FIGURE 8 TORQUE COEFFICIENT CURVE OF ROTOR WITH FEATHERING MOTION

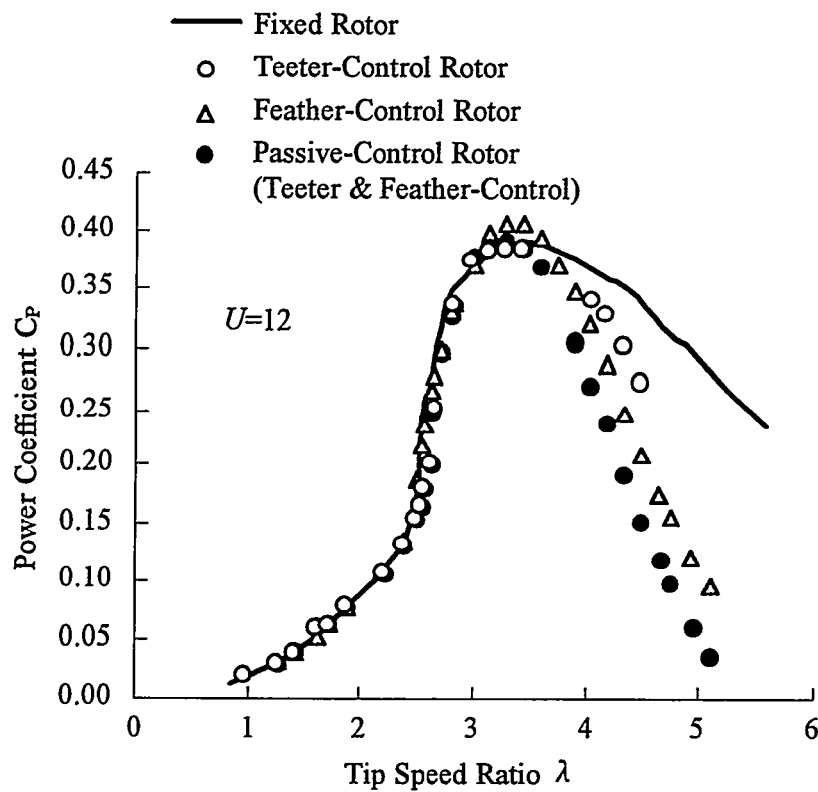


FIGURE 9 COMPARISON OF PERFORMANCE OF THE ROTOR WITH FIXED PITCH, TEETER CONTROL, FEATHER CONTROL AND COMBINATION OF TEETER AND FEATHER CONTROLS

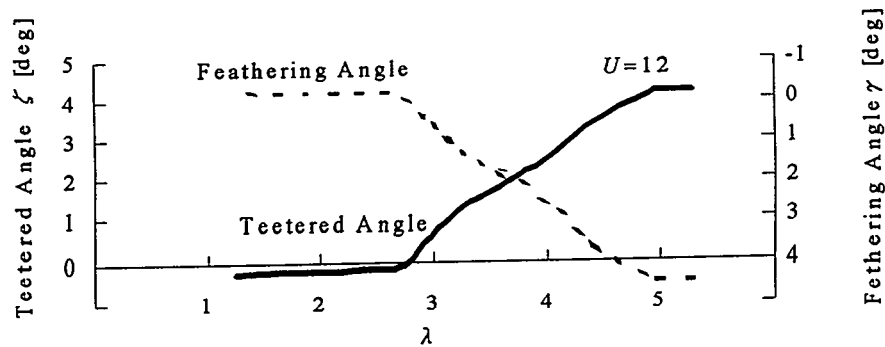


FIGURE 10 RELATIONSHIP BETWEEN TEETERED ANGLE AND FEATHERING ANGLE FOR PASSIVE CONTROL ROTOR

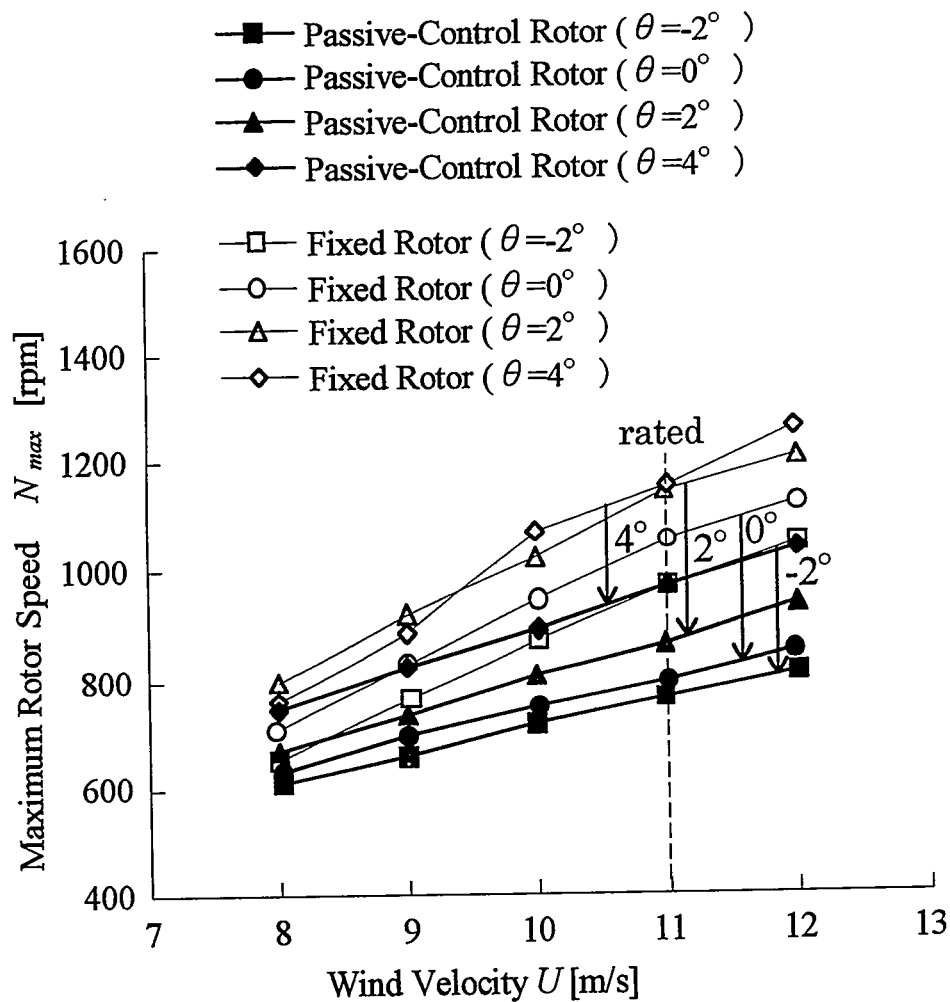


FIGURE 11 SUPPRESSION OF ROTOR SPEED DUE TO PASSIVE CONTROLLED HUB FOR DIFFERENT INITIAL SETTING PITCH ANGLE θ

A 3-D AERODYNAMIC METHOD FOR THE ANALYSIS OF ISOLATED HORIZONTAL-AXIS WIND TURBINES

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ABSTRACT

In most existing performance-analysis methods, wind turbines are considered isolated so that interference effects caused by other rotors or by the site topography are neglected. The main objective of this paper is to propose a practical 3-D method suitable for the study of these effects, in order to optimize the arrangement and the positioning of Horizontal-Axis Wind Turbines (HAWTs) in a wind farm. In the proposed methodology, the flow field around isolated HAWTs is predicted by solving the 3-D, time-averaged, steady-state, incompressible, Navier-Stokes equations in which the turbines are represented by distributions of momentum sources. The resulting governing equations are solved using a Control-Volume Finite Element Method (CVFEM). The fundamental aspects related to the development of a practical 3-D method are discussed in this paper, with an emphasis on some of the challenges that arose during its implementation. The current implementation is limited to the analysis of isolated HAWTs. Preliminary results have indicated that the proposed 3-D method reaches the same level of accuracy, in terms of performance predictions, than the previously developed 2-D axisymmetric model and the well-known momentum-strip theory, while still using reasonable computer resources. It can be considered as a useful tool for the design of HAWTs. Its main advantages, however, are its intrinsic capacity to predict the details of the flow in the wake, and its capabilities of modelling arbitrary wind-turbine arrangements and including ground effects.

1. INTRODUCTION

After some unsuccessful attempts at constructing and operating very-large-scale isolated wind turbines, the recent trend is to construct wind farms of medium-size machines. The strategy currently used during the conception of such wind farms consists in installing the turbines far from each other in order to minimize the interference effects. This practice results in very sparse wind farms where the wind energy potential of a site is inefficiently used. It is justified by the performance losses associated to the wake effects, which are significant in dense arrangements. However, an appropriately designed dense and staggered arrangement of the turbines is expected to have a production similar to a sparse arrangement but would occupy less land. This can result in a significant economy in operating costs. Various aerodynamic methods, appropriate for the conception of isolated turbines, are available to designers [1, 2, 3, 4, 5]. However, efficient and accurate methods for the analysis of a dense cluster which include the effects of the 3-D turbulent turbine wakes are not available.

A method that includes the essential ingredients for the successful performance predictions of wind turbines in a dense arrangement is presented in this paper. In the proposed method, the flow field of the wind farm is predicted by solving the 3-D, time-averaged, steady-state, incompressible Navier-Stokes equations. The turbines are represented by distributions of momentum sources, a technique introduced by Rajagopalan [6] and Rajagopalan and Fanucci [7]. This is a general formulation which can be applied, in principle, to horizontal-axis and vertical-axis wind turbines and can include the effects of hubs, towers and ground topography. The Navier-Stokes equations are solved

using the 3-D Control-Volume Finite Element Method (CVFEM) of Saabas and Baliga [8]. The 3-D procedure proposed in this paper is an extension of the previously developed 2-D axisymmetric method [9, 10]. Although this 3-D method is very similar in concept to the axisymmetric one, some new challenges arose during its implementation, such as: (i) the management of the limited computer resources and (ii) the non-conformity between the rotor geometry (cylindrical) and the coordinate system used for the simulations (Cartesian). These aspects are discussed in the paper. The current implementation of the proposed methodology is restricted to the analysis of isolated HAWTs. Comparisons between the performance predictions obtained with the proposed 3-D formulation and those of the previously developed 2-D axisymmetric method and momentum-strip theory are presented to illustrate the accuracy of the methodology.

2. MATHEMATICAL MODEL

The flow around an isolated HAWT is governed by the unsteady 3-D Navier-Stokes equations which have to be solved in a domain with moving boundaries. Analytical solutions of such a problem are hardly possible while numerical solutions represent a formidable task on today's computers. However, a more tractable model producing meaningful results can be obtained by time-averaging the governing equations over the rotor period of rotation and by representing the turbine with momentum sources.

The derivation of the governing equations and momentum sources is based on time-averaging techniques and the blade-element theory. The interested reader is referred to the works of Rajagopalan [6] and Rajagopalan and Fanucci [7] for a detailed derivation of the source terms of vertical-axis wind turbines. In the case of horizontal-axis wind turbines, of interest here, the derivation is very similar and the reader is referred to Figure 1 for the definition of the various parameters involved in the evaluation of the momentum sources.

2.1 Governing equations

The flow around an HAWT can be represented by the 3-D, time-averaged, steady-state, incompressible Navier-Stokes equations:

$$\frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \quad (1)$$

$$\frac{\partial}{\partial x}(\rho uu) + \frac{\partial}{\partial y}(\rho vu) + \frac{\partial}{\partial z}(\rho wu) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\mu_e \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\mu_e \frac{\partial u}{\partial y}) + \frac{\partial}{\partial z}(\mu_e \frac{\partial u}{\partial z}) + (S_T)_u \quad (2)$$

$$\frac{\partial}{\partial x}(\rho uv) + \frac{\partial}{\partial y}(\rho vv) + \frac{\partial}{\partial z}(\rho wv) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}(\mu_e \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(\mu_e \frac{\partial v}{\partial y}) + \frac{\partial}{\partial z}(\mu_e \frac{\partial v}{\partial z}) + (S_T)_v \quad (3)$$

$$\frac{\partial}{\partial x}(\rho uw) + \frac{\partial}{\partial y}(\rho vw) + \frac{\partial}{\partial z}(\rho ww) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}(\mu_e \frac{\partial w}{\partial x}) + \frac{\partial}{\partial y}(\mu_e \frac{\partial w}{\partial y}) + \frac{\partial}{\partial z}(\mu_e \frac{\partial w}{\partial z}) + (S_T)_w \quad (4)$$

The four dependent variables are the velocity vector $\vec{V}$ (having the components u , v , and w in the x , y , and z directions respectively) and the pressure p . The source terms $(S_T)_u$, $(S_T)_v$, $(S_T)_w$ are the x -, y - and z -components of the mutual time-averaged force, exerted by the fluid and the blade on one another, per unit volume of fluid. They will be referred to as the momentum-source term. The fluid density is represented by ρ , and its dynamic viscosity by μ . The effective viscosity μ_e is the sum of the dynamic viscosity μ and the turbulent eddy viscosity μ_T .

At this early stage of development, the turbulent eddy viscosity has been set to a constant value, corresponding to the turbulent eddy viscosity of the neutral undisturbed atmospheric boundary layer at the hub height. Although the turbulence generated by the turbine itself is not included,

accurate performance predictions can be obtained using this assumption in the case of isolated HAWTs since their performances are not highly influenced by the details of their wakes. However, when a turbine is located behind another one, the turbulent wake has a significant influence and more advanced turbulence modelling is needed in order to obtain accurate performance predictions for the downwind turbine [10]. Nevertheless, the proposed mathematical model still includes some of the essential elements for accurate performance predictions of wind farms. The major features of the proposed model are (i) its capacity to model the details of the wake behind the turbines and (ii) its implicit introduction of the interferences between the rotors.

The development of an analytical expression for $(S_T)_u$, $(S_T)_v$, and $(S_T)_w$, the x -, y -, and z -components of the time-averaged volumetric source terms is presented next.

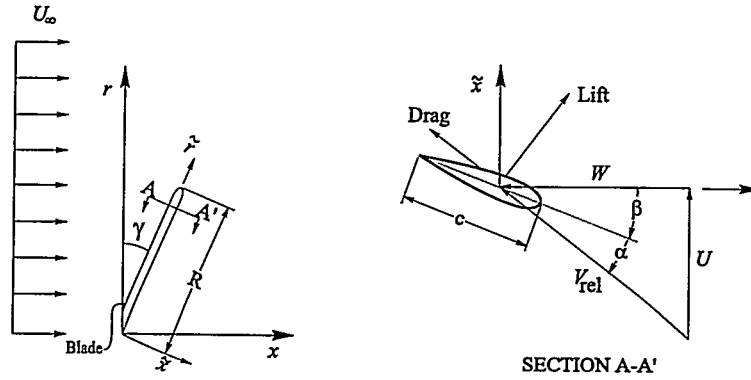


Fig. 1: Wind-turbine geometric parameters

2.2 Rotor representation

The momentum-source terms are evaluated using the two-dimensional blade-element theory. The turbine is composed of B blades of length R , having a coning angle γ . The blade chord c and twist angle β can vary radially. The turbine rotational speed is Ω . Figure 1 presents the forces due to lift and drag over a blade section at a given radial location. By decomposing these forces onto the $\tilde{x}$ - and θ -axes, the expressions of the forces acting on an infinitesimal blade length $d\tilde{r}$ are:

$$d\vec{F}_\theta(\tilde{r}, \theta) = \frac{\rho V_{rel} c d\tilde{r}}{2} [U C_L - W C_D] \vec{\theta} \quad (5)$$

$$d\vec{F}_x(\tilde{r}, \theta) = \frac{\rho V_{rel} c d\tilde{r}}{2} [W C_L + U C_D] \vec{x} \quad (6)$$

where $V_{rel} = \sqrt{U^2 + W^2}$, $U = u \cos \gamma - v \sin \gamma$, $W = r\Omega - w$ and $\vec{\theta}$ and $\vec{x}$ are the unit vectors in the directions of the $\tilde{x}$ - and θ -coordinates, respectively. C_L and C_D are the static lift and drag coefficients of the blade-defining airfoil and are, in general, functions of the angle of attack α and the local Reynolds number $Re_c (= \frac{\rho V_{rel} c}{\mu})$. In the proposed model, these coefficients can be taken from experimental data or numerical results obtained over the appropriate airfoil.

It is to be noted that the momentum-source terms are non-zero only on the rotor swept area defined by $\tilde{x} = 0$, $0 \leq \tilde{r} \leq R$, $0 \leq \theta \leq 2\pi$. In the case of a HAWT with a coning angle γ , the rotor swept area is a right circular cone with a base radius given by $R \cos \gamma$.

The most natural coordinate system for the analysis of HAWTs is clearly the cylindrical coordinate system. However, in order to model ground effects and arbitrary arrangements of turbines, the Cartesian coordinate system must be used. This prescription on the coordinate system has significant implications in the integration of the momentum sources over the conical surface swept

by the blades. Further development of the momentum-source terms is directly related to the numerical method and the domain discretisation, and is therefore delayed until the description of the CVFEM is completed (see Section 3.4).

3. NUMERICAL METHOD

The proposed numerical method is a CVFEM based on the primitive-variables, co-located, equal-order formulation of Saabas and Baliga [8]. Detailed description of this CVFEM, pertaining to internal three-dimensional turbulent flows, is available in the work of Saabas [11]. Aspects relevant to the successful simulation of the flow around a wind turbine are presented in Refs. [9] and [10].

3.1 Calculation domain and boundary conditions

The calculation domain consists of a rectangular box that includes the wind turbine, as represented in Figure 2a. Boundary conditions for u, v, w and p have to be prescribed on the six faces of the domain.

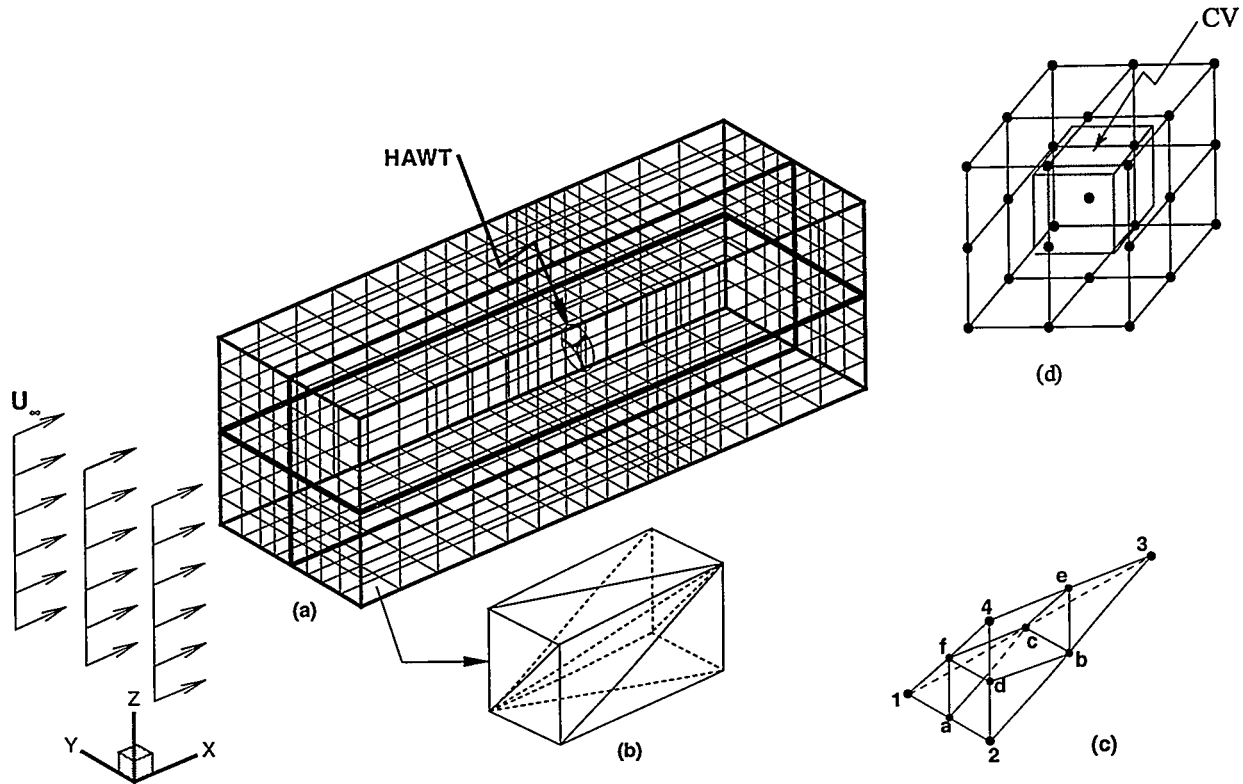


Fig. 2: Computational domain and grid topology

Inlet boundary: The inlet boundary is a $y-z$ plane located upstream of the wind turbine. In this plane, the three velocity components are given by the known freestream wind speed while the pressure is calculated from the discretized continuity equations.

Outlet boundary: The outlet boundary is a $y-z$ plane located downstream of the wind turbine. In this plane, the pressure is assumed to be uniform and given while the three velocity components are computed from the discretized momentum equations obtained using the outflow treatment of Patankar [12].

Top, bottom and side boundaries: The top and bottom boundaries are x - y planes while the side boundaries are x - z planes. In these planes, the velocity is set to its freestream value. Pressure is calculated from the discretized continuity equations.

3.2 Discretization of the calculation domain

As illustrated in Figure 2, the discretization of three-dimensional calculation domains proceeds in two steps. The domain is first divided into eighth-node bricks (see Figure 2a). Six tetrahedral elements are then formed within each of the bricks (see Figure 2b). Each tetrahedron is defined by four nodes at which all dependent variables are calculated (nodes 1, 2, 3, and 4 of Figure 2c). Once this discretization is complete, control-volume surfaces are formed within each element. In order to form the control volumes, the mid-points of the edges of the tetrahedral elements must first be defined. These are points a to f in Figure 2c. These midpoints are then joined so as to form three control-volume surfaces within each element. As shown in Figure 2c, two triangular surfaces and one four-node surface are formed. These control-volume surfaces subdivide the element into four subvolumes, of which two are one-eighth of the total element volume, and two are three-eighths of the total element volume. As the elements are assembled, polyhedral control volumes are formed around the nodes as indicated in Figure 2d.

3.3 Discretization equations

The system of equations solved by the CVFEM is composed of algebraic approximations to the integral conservation equations. These integral conservation equations are obtained by applying the conservation principle (Eqs. (1) to (4)) to the control volumes constructed using the procedure described in Section 3.2. A compact representation of the integral momentum discretized equations for a typical control-volume can be written as:

$$a_p^u u_p = \sum_{nb} a_{nb}^u u_{nb} + b^u - \overline{F_x}|_{CV} \quad (7)$$

$$a_p^v v_p = \sum_{nb} a_{nb}^v v_{nb} + b^v - \overline{F_y}|_{CV} \quad (8)$$

$$a_p^w w_p = \sum_{nb} a_{nb}^w w_{nb} + b^w - \overline{F_z}|_{CV} \quad (9)$$

Details concerning the derivation of the algebraic approximations of the convection and diffusion terms in Eqs. (1) to (4) can be found in Refs. [8] and [11]. In the next section, the algebraic approximations for the momentum-source terms are derived.

3.4 Rotor representation

The contribution of the momentum-source terms to a given control-volume integral momentum-conservation equations ($\overline{F_x}|_{CV}$, $\overline{F_y}|_{CV}$, $\overline{F_z}|_{CV}$) is an integration of the blades forces over a surface defined by the intersection of the given control-volume and the rotor swept area. With the polyhedral control-volumes used in this work, this integration surface is simply a quadrilateral surface. The projection of a typical integration surface onto the y - z plane is illustrated in Figure 3a. This surface will be referred to as the control-volume swept surface. Its projection onto the y - z plane will be denoted A_{CV} .

The first step in the evaluation of the contribution of the momentum-source terms to a given control-volume integral momentum-conservation equation is the decomposition of $d\vec{F}_\theta$ and $d\vec{F}_x$ in

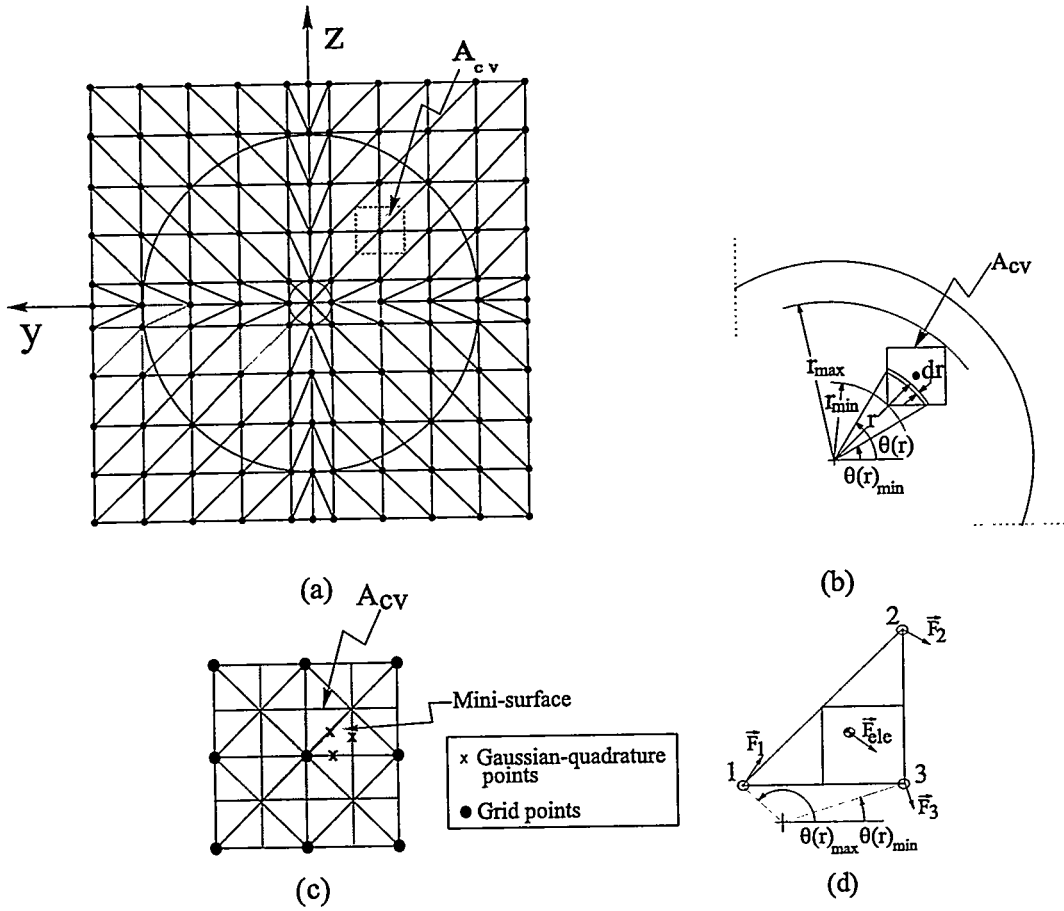


Fig. 3: Integration Surface for the Momentum-Source Terms

the direction of the three coordinates x , y and z :

$$dF_x(\tilde{r}, \theta) = d\vec{F}_\theta \cdot \vec{i} + d\vec{F}_{\tilde{r}} \cdot \vec{i} \quad (10)$$

$$dF_y(\tilde{r}, \theta) = d\vec{F}_\theta \cdot \vec{j} + d\vec{F}_{\tilde{r}} \cdot \vec{j} \quad (11)$$

$$dF_z(\tilde{r}, \theta) = d\vec{F}_\theta \cdot \vec{k} + d\vec{F}_{\tilde{r}} \cdot \vec{k} \quad (12)$$

where $\vec{i}$, $\vec{j}$, $\vec{k}$, are three unit vectors in the direction of x , y and z , respectively. In order to integrate, for example, the projected force $dF_x(\tilde{r}, \theta)$ over the control-volume swept area as presented in Figure 3b, it is convenient to use the independent variable r instead of $\tilde{r}$:

$$dF_x(r, \theta) = f_x(r, \theta) \frac{1}{\cos \gamma} dr \quad (13)$$

where $f_x(r, \theta) = \frac{\rho V_{relc}}{2} [WC_L + UC_D] \cos \gamma$.

For a constant radius r , we can integrate $dF_x(r, \theta)$ over the blade path lying in the control-volume of interest, defined by $\theta(r)_{min}$ and $\theta(r)_{max}$ (see Figure 3b), to obtain the averaged force in the x -direction, $d\vec{F}_x(r)$, over this blade path:

$$d\vec{F}_x(r) = \frac{1}{\Delta\theta(r)} \int_{\theta(r)_{min}}^{\theta(r)_{max}} f_x(r, \theta) \frac{1}{\cos \gamma} d\theta dr \quad (14)$$

where $\Delta\theta(r) = \theta(r)_{\max} - \theta(r)_{\min}$

The time ratio for which the blades are present in this blade path is $\frac{B\Delta\theta(r)}{2\pi}$. Therefore, the time-averaged force exerted by the fluid on the blades, $\overline{F_x}|_{CV}$, in the x -direction and over the control volume of interest, can be written as:

$$\overline{F_x}|_{CV} = \int_{r_{\min}}^{r_{\max}} \frac{B}{2\pi} \int_{\theta(r)_{\min}}^{\theta(r)_{\max}} f_x(r, \theta) \frac{1}{\cos\gamma} d\theta dr \quad (15)$$

The surface integrand dA for the conical rotor swept area is given by:

$$dA = \frac{r}{\cos\gamma} dr d\theta \quad (16)$$

Substituting this expression for $dr d\theta$ into Eq.(15), the expression of the time-averaged force exerted by the fluid on the blades, in the x -direction and over the control volume of interest reduces to:

$$\overline{F_x}|_{CV} = \frac{B}{2\pi} \int_{A_{CV}} \frac{f_x(r, \theta)}{r} dA \quad (17)$$

where A_{CV} is the projection of the control-volume swept area onto the y - z plane. The same procedure can be applied to the y - and z -components of the aerodynamic forces in order to obtain the expressions for $\overline{F_y}|_{CV}$ and $\overline{F_z}|_{CV}$.

For a given grid refinement, the extension from 2-D axisymmetric to 3-D modelisation significantly increases the number of grid points. Thus, in order to keep the method efficient and the computational time reasonable, the refinement of the 3-D grid has to be restricted. However, some characteristics of the momentum-source terms lead to the requirement of a finer grid in order to accurately represent the effects of the rotor.

In a control-volume swept area near the axis of rotation as shown in Figure 3d, large variations in θ are observed, resulting in similar variations in the direction of the aerodynamic forces (denoted $\vec{F}$ in Figure 3d). Thus, integrating with the assumption that the centroidal value of the aerodynamic forces prevails over the element will lead to a poor evaluation of the momentum-source terms.

Furthermore, Figure 3a shows the poor adequacy between the boundary of the rotor swept area and the grid points. Inevitably, on a realistic (coarse) 3-D grid, the numerical integration procedure will falsely subtract or add significantly large amounts to the exact values of the momentum sources for the control volumes near the boundaries of the rotor swept area.

These two difficulties related to the use of a 3-D formulation can be minimized by the use of a very fine grid. However, the use of such a grid would require unrealistic computer resources. A more efficient way of tackling these difficulties is to superimpose, on the surface where the momentum source integration is performed, a finer grid over the original one. The new grid is composed of triangular mini-surfaces which are subdivisions of the original control-volume swept surface A_{CV} (see Figure 3c). The flow field is not solved over this finer grid, its objective is to enable a more precise integration of the momentum sources at a low computational cost. The numerical integration using three-point Gaussian quadrature is performed over each triangular mini-surface.

4. RESULTS

The results presented in this section are aimed at demonstrating the capacity of the 3-D methodology to accurately predict the performances of isolated HAWTs and to analyse wind farms. To this effect, the details of the computed flow field in the vicinity of an isolated HAWT are shown, and

comparisons between the predictions of the proposed 3-D method, those of the previously developed 2-D axisymmetric method and those of the momentum-strip theory are presented.

The simulations presented in this section have been realized for the NASA/DOE Mod-0 100-kW Experimental HAWT [13] operating at a rotational speed of 40 rpm and a blade pitch angle of 3° . The air density ρ was assumed to be 1.25 kg/m^3 . The effective viscosity μ_e was set to $1.8 \cdot 10^{-5} \text{ N} \cdot \text{s/m}^2$ for the turbine performance analysis and $5.4 \text{ N} \cdot \text{s/m}^2$ for the flow visualisation reproducing laminar and turbulent atmospheric boundary layer conditions, respectively. Based on a grid independence study, a nonuniform ($40 \times 38 \times 38$) grid was chosen for calculations. Refinement was applied to the grid in the immediate vicinity of the turbine in order to capture the sharp variations of the flow properties present in that region.

Figure 4 shows a comparison between the performance predictions produced by the proposed 3-D methodology, the 2-D axisymmetric method and the momentum-strip theory. Because of the difficulties inherent to the use of a 3-D formulation (see Section 3.4), one of the main concerns in the extension from 2-D to 3-D was to maintain the same level of accuracy while not increasing the grid refinement. Results have shown that, for a similar grid refinement, the 2-D and 3-D methods yield the same level of accuracy, which demonstrates the validity and efficiency of the proposed 3-D implementation. The 2-D and 3-D methods are also in good agreement with the momentum-strip theory. These results show the accuracy of the 3-D method in predicting performances for isolated HAWTs. However, the main motivation in developing the proposed method resides in its inherent capacity, through the calculation of the details of the flow field around the turbines, of modelling rotor/rotor, rotor/ground, and rotor/tower interactions. Figures 5 and 6 illustrate the capacity of the proposed methodology to produce the details of the flow behind a wind turbine, which constitutes one of the essential features for the successful analysis of wind farms.

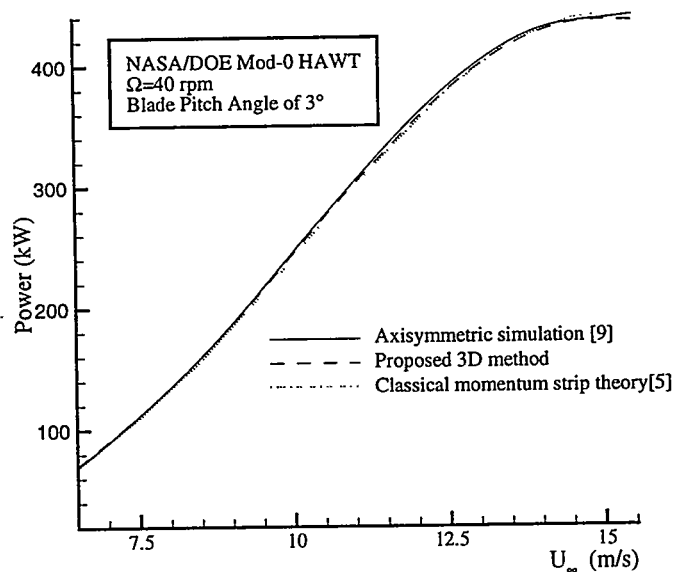


Fig. 4: Performance Predictions

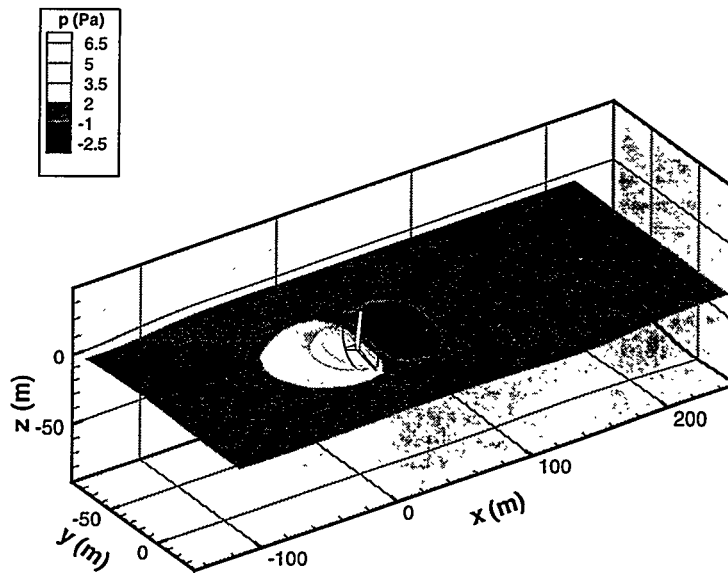


Fig. 5: Pressure field

5. CONCLUSION

A fully 3-D methodology has been developed for the predictions of the flowfield, the performance and interference effects of Horizontal-Axis Wind Turbines (HAWTs). Through the analysis of the NASA/DOE Mod-0 100-kW Experimental HAWT, the accuracy of the proposed method in terms of performance prediction has been demonstrated. Moreover, the developed 3-D procedure has proven to overcome the difficulties associated with the use of a 3-D formulation by using limited computer resources.

Although the method presented in this paper includes some of the important ingredients needed for the successful analysis of dense cluster arrangements of HAWTs, additional features have to be included before its application for the performance optimization of wind farms. An appropriate turbulence model should be selected and implemented in order to obtain accurate performance predictions for turbines located behind other ones. Nevertheless, the 3-D formulation produces performance predictions for isolated HAWTs with the same level of accuracy than the well-known momentum-strip theory. It can be considered to be a useful tool for the design of HAWTs.

ACKNOWLEDGEMENT

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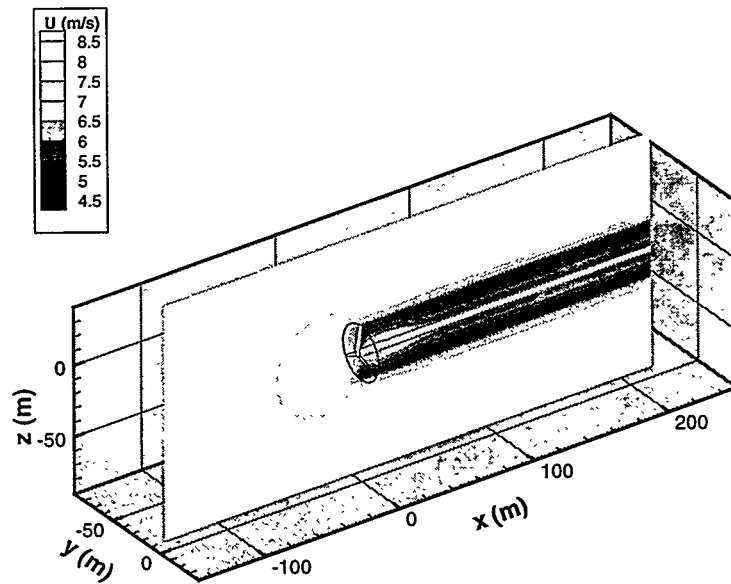


Fig. 6: Streamwise velocity field

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AN ANALYTICAL INVESTIGATION OF THE PERFORMANCE OF WIND-TURBINES WITH GYROCOPTER-LIKE ROTORS

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ABSTRACT

The performance was predicted of a wind-turbine, intended for electrical power generation, the rotor of which is similar in configuration to the rotor of an autogyro or gyrocopter as originated by Cierva. Hence the rotor axis of spin is tilted downwind, for maximum power production, by an angle of 40° to 50° relative to the vertical with power regulation by modulation of the tilt angle. Because the rotor of a Cierva turbine generates lift the simple, non-twisted, fixed-pitch blades "fly" and are self supporting thereby eliminating flap-wise bending moments when the blades are hinged at their roots. It was found from the analysis that it is possible to reduce tower bending moments substantially relative to a conventional horizontal axis turbine of equal power output and also, for equal maximum hub heights and blade tip altitudes, a Cierva turbine is capable, at a prescribed wind speed, of a greater power output than a conventional horizontal axis machine.

NOMENCLATURE

C_L	Airfoil two-dimensional lift coefficient
D	Rotor diameter
F_x	Force acting on the rotor due to the flow in the flow (wind) direction
F_y	Force generated by rotor normal to flow (wind) direction
T	Thrust force resulting from F_x and F_y
W	Deadweight active on tower top
α	Airfoil angle of incidence
ϕ	Rotor tilt angle (CWT)

Subscripts and Abbreviations

CWT	Cierva wind-turbine
HAWT	Horizontal axis wind-turbine

INTRODUCTION

The late Juan de la Cierva is recognised as the originator of the autogyro, or gyrocopter, type aircraft [1]. A gyrocopter is fairly similar in appearance to a single-rotor helicopter. In modern gyrocopters the rotor provides all the lift required to support the aircraft. In the case of the autogyro, or gyrocopter, the lift-generating rotor is driven, when such an aircraft is in flight, by the passage of the vehicle through the air. The rotor operates, therefore, as an unloaded wind-turbine with the aircraft being propelled forward by means of a conventional propeller driven by the vehicle engine. To achieve autorotation of the lift-generating rotor the axis of this component is tilted slightly downwind of vertical, ie. the opposite situation to that of a helicopter. This system has the advantage of permitting the use of a very simple, fixed-pitch rotor. A disadvantage of the gyrocopter relative to that of a helicopter is that a gyrocopter flying in still air cannot hover. However, due to the spinning rotor, the landing distance is very short and, provided engine power

is used to pre-spin the rotor prior to take-off, so also is the take-off distance.

The angle of tilt to maintain the cruise mode autorotation of the lift-rotor of a gyrocopter is typically in the region of only about 10° downwind of vertical. A greater tilt angle would allow net power to be extracted from the rotor. However the extraction of net power in this manner is of no practical significance with respect to the operation of a gyrocopter. Nevertheless a gyrocopter type rotor could, conceivably, be employed as a wind turbine operating at greater tilt angles than those necessary to achieve no-load autorotation. Possible advantages of a Cierva wind turbine (CWT) are the use of simple, probably symmetric cross-section, non-twisted, blades: power regulation by modulation of the rotor tilt angle ϕ : the relief of blade-root flap-wise bending moments due to the blades being effectively "in flight": the possibility of using rotor aerodynamic lift force to assist in offsetting tower buckling loads and also, for a prescribed maximum scan, or sweep, of the rotor-blade tips in the vertical direction, the possibility of employing a rotor of larger diameter than that of a conventional horizontal axis wind turbine (HAWT) [2,3]. The information reported here represents, for the greater part, a summary of many of the findings of a very rudimentary study of the CWT concept [2] and a subsequent much more thorough, but still preliminary, investigation [3].

CIERVA-TURBINE CONFIGURATIONS

Figure 1 shows, diagrammatically, a comparison of a HAWT and a CWT of equal hub height for which $D_{CWT} \sin \phi = D_{HAWT}$. The magnitude of the "visual intrusion" assessed on the basis of the height above ground level attained by the upward sweep of the blade tips is equal for both types of machine. It is clear that the projected area of the CWT in the wind flow direction is greater than that of the HAWT by a factor of $\text{Cosec } \phi$ and if both machines achieved equal power coefficients the power output of the CWT at a prescribed wind speed would be greater than that of the HAWT by the same factor. In reality the power coefficient of the CWT is likely to be less than that of the HAWT implying that the power output of the CWT could be less or more than that of the HAWT depending upon the magnitude of the tilt angle ϕ and other factors. Clearly a detailed performance analysis is required in order to resolve this quantitatively.

An alternative to supporting a CWT on a conventional vertical tower is to employ a variably inclinable tower as indicated in Fig. 2(a). An arrangement of this type not only permits the tilt angle, ϕ , to be adjusted by varying the tower inclination but also allows the speed step-up gearbox, if one is employed, and the alternator to be mounted at the tower base driven, from the rotor, by a shaft within the tower. It also, for a fixed-pitch rotor, results in only one major lubricated, and wearable, component, namely the upper rotor bearing, being located at the tower top. It is expected that the rotor blade flap-hinges will probably be of the elastomeric type currently employed in some helicopters and the only maintenance required by these will be periodic replacement at infrequent intervals. The inclinable tower system also allows the yaw bearing to be located at the tower base.

The resultant moments on the yaw bearing of an inclinable tower should prove to be manageable due to the comparatively light load carried by the tower and also, when the machine is operating, substantial bending moment relief due to the action of the aerodynamic lift force F_y . It may also be possible to arrange to lower the tower such that the rotor rests on the ground. This not only eases tower-top maintenance but also provides protection from damage due to very strong winds. This would, therefore, obviate the need for a heavy construction merely to ensure survival in occasional gale or hurricane conditions. Such an arrangement forces the selection of a two-bladed rotor and also a braking mechanism that will ensure that the stationary rotor blades are always parallel to the ground when the machine is lowered. A braking system with this characteristic has already been developed by the Nedwind company for off-shore HAWT type machines.

Figure 2(b) shows how an inclinable tower can be arranged in such a way that the rotor blade tips do not

approach the ground too closely at the maximum tilt condition. It can also be seen that the alternator, gearbox and braking system serve to help counter-weight the tower and rotor when the tower is inclined. An hydraulic cylinder is shown, in Fig. 2(b), as the means for raising or lowering the tower. The electric-motor driven pump supplying the hydraulic cylinder would be controlled such as to trim the turbine output to maintain the maximum permissible power of the machine, by reducing the tilt angle ϕ , at wind speeds in excess of the rated value. Control inputs for the machine would also be obtained from the anemometer and the wind-direction indicator vane.

ANALYTICAL TREATMENT

The prime purpose of the analytical work was to compare CWT performances with those of corresponding HAWT units. Two separate computer programs were employed. HAWT performances were evaluated using an available, 1987, version of PROPCODE, a program issued by the National Renewable Energy Laboratory, generally accepted as a standard analytical tool for evaluating HAWT basic aerodynamic performances. A new program, CIERVACALC, based to some extent on features of PROPCODE, was developed by the second author to evaluate CWT performances.

In order to conduct the CWT versus HAWT comparison as consistently as possible the airfoil section selected for use with both turbine types was the well known, symmetrical, NACA 0012. The performance of a smooth, clean, airfoil of this type, operating at a representative chord-based Reynolds number of 3×10^6 , was obtained from data published by Abbott and von Doernhoff [4]. The NACA 0012 section is sometimes used for the blades of autogyros and also helicopters and hence it represents a reasonable choice for CWT blades. However this choice is less defensible for HAWT blades. Normally specially developed sections are employed. However, at the fundamental theoretical level the lift curve slope, $dC_L/d\alpha$, can be expected to have a linear gradient, well prior to stall, of 2π per radian or 0.1097 per degree of incidence for all thin two-dimensional or infinite aspect ratio, airfoils. This gradient is closely representative of most real airfoils and is almost exactly the lift curve slope of the NACA 0012 section. The characteristic C_L versus α curve of the NACA 0012 section differs from that of some dedicated HAWT sections in that stall occurs at a higher C_L value for the former than for the latter. However, since the performance comparison of the CWT will be made with pitch-regulated HAWT units the high C_L values occurring at high wind speeds, corresponding to low tip-speed ratios, will not affect, significantly, overall HAWT performance predictions. Furthermore the NACA 0012 section tends to have a lower two-dimensional drag coefficient than most, relatively thick, dedicated HAWT blade cross-sections: this favours, slightly, HAWT performances predicted on the basis of a NACA 0012 section.

HAWT Program PROPCODE

The PROPCODE software was originated by the AeroEnvironment Corporation for the US Wind Energy Research Center where it was modified slightly to increase operational effectiveness. The modified version is identified as PROPSH [5]. In general terms the modified PROPCODE has the capability of producing either a dimensional or a non-dimensional output and takes account of such factors as cross-flow effects due to yaw or rotor tilt, features omitted from the original version. The PROPCODE software accommodates, as an input, airfoil data which, for the cases of interest here, corresponded to a digital rendition of the two-dimensional performance of the NACA 0012 section. The PROPCODE program [5] also incorporates lift and drag data for a flat plate. These data are employed for angles of incidence greater than those at which stall occurs when, as for the NACA 0012 case, no specific airfoil data are available. PROPCODE employs up to 20 radial stations and, when yaw and earth boundary layer velocity variations are ignored as was the case for the HAWT performance analyses reported here, the program models HAWT rotors as a series of multiple, coaxial annular, actuator discs in the manner described, for example, by Sharpe (Freris [6]). PROPCODE also incorporates Glauert's empirical approximation [7] made to counter the inability of inviscid

flow theory to model correctly viscous (irreversible) effects in the rotor wake for conditions giving rise to values of the axial induction factor in excess of approximately 0.4. The use of the Glauert empirical relationship typically comes into play only at low wind speeds, corresponding for most wind-electric machines to a high tip-speed ratio condition, and low power outputs. Hence the inclusion of Glauert's empirical approximation has but a relatively small quantitative influence on typical HAWT predictions of output power.

Most users of PROPCODE appear to favour employing the Prandtl blade tip-loss model [6,7], a built-in option. However, for the work reported here it was decided to employ an alternative, and simpler, built-in routine in which the lift of the outer 3% of each blade was set to zero. The reason for changing from the Prandtl tip-loss model to the "3% concept" was that it was expected to be easier to incorporate the "3% concept" in the CIERVACALC code than the former. The "3%", or effective radius, tip-loss model has also been used for rotor-craft such as helicopters and autogyros [8]. Figure 3 shows a comparison of the influences on the performance of a HAWT of the Prandtl and the "3%", or effective radius, models. A datum curve is also presented in Fig. 3 showing the performance when tip losses are entirely ignored. As can be seen the difference in performance predictions between the Prandtl and the effective radius techniques was negligible. Yet another PROPCODE feature is to include, if need be, rotor coning. This option was not required for the HAWT analytical work reported here because, in each case, the rotor was considered to be planar and normal to the oncoming flow. More details relating to PROPCODE and the adaptation of this program for the study reported here have been given by Brophy [3].

CWT Code CIERVACALC

The CIERVACALC code, developed by the second author, was, in part, based on PROPCODE with the major difference being the ability of CIERVACALC to accept conditions in which the flow is massively tangential to the plane of the rotor disc. To incorporate this feature use was made of a classical analysis, due to Glauert [9], of the aerodynamics of the autogyro specifically Glauert's expression for induced velocity based on an analogy between the autogyro rotor, considered as a modified actuator disc, and an elliptically loaded circular wing. The Glauert expression for induced velocity has been shown by Bramwell, as reported by Seddon [8], to be well supported by experimental evidence. At zero tilt angle, ϕ , the Glauert's expression yields the correct conditions, at zero flight speed, corresponding to a hovering helicopter and for $\phi = 90^\circ$ it also reduces to the correct expression for the induced velocity applicable to a horizontal axis wind-turbine.

The blades of a CWT, or autogyro, experience different flow conditions, and variable incidence angles, depending upon whether a blade is advancing or retreating relative to the oncoming flow. Hence CIERVACALC is specifically arranged to take into account azimuthal variations in flow conditions while operating in a multi-stream-tube mode in a manner similar to PROPCODE.

Computational features included in PROPCODE but omitted from CIERVACALC because they were not found to be essential for representative CWT operating regimes were; tangential induction leading to valuation of the tangential induction factor, Glauert's empirical modification of the classical momentum equation and also the option of employing Prandtl's tip-loss model. The "3%", or effective radius, tip-loss model was programmed integrally, into CIERVACALC.

As at least a partial test of CIERVACALC this code was employed to evaluate the performance of a constant rotational-speed CWT at a tilt angle, ϕ , of 90° . This machine, which was of 30 m rotor diameter, employed fixed pitch, non-twisted, blades of simple rectangular planform set at a pitch angle of zero degrees. The rotor solidity was 0.075. The predicted performance obtained in this way was compared with a corresponding result, for similar blading, using PROPCODE with both the Glauert empirical extension of the momentum equation and the tangential induction features suppressed in order to conform to the restrictions implicit in

CIERVACALC. The results of this comparison are presented in Fig. 4 showing that the two predicted performances are virtually identical.

The influence of dynamic stall on the performance of a CWT was investigated briefly but a routine to handle dynamic stall was not included in CIERVACALC. It appeared that the dynamic stall phenomenon while it serves to delay, transiently, flow separation at high angles of attack may also delay flow reattachment [10,11] hence it is not clear, without further work, whether or not significant benefits, or otherwise, can be obtained from dynamic stall. High angle of attack situations arising with CWT operation were handled in CIERVACALC by using (static) flat-plate aerodynamic drag coefficient characteristics, as in PROPCODE, in conjunction with actual lift coefficient data available for the NACA 0012 section used for the rotor blades [12]. More details relating to CIERVACALC than can be included here are available elsewhere [3].

PERFORMANCE PREDICTIONS

Performance predictions were compared for HAWT and CWT machines with rotor solidities of 0.1, 0.075 and 0.05. All the HAWT machines were of the variable pitch type with either non-twisted rectangular planform blades, optimally twisted rectangular blades or half-tapered, optimally twisted, blades for which the chord at the blade tip was half that at the blade root. For all the CWT machines the blades were non-twisted and of rectangular planform. They were also of fixed pitch with a pitch angle of zero. For all machines the blade cross-section employed was, as stated previously, NACA 0012. The relationship between the diameters of the HAWT and CWT rotors was such that $D_{\text{CWT}} \sin \phi = D_{\text{HAWT}}$ for various prescribed values of ϕ . For the performance comparisons presented here ϕ was 40° . Hence for the HAWT rotor diameter of 30 m the corresponding CWT rotor diameter was $D_{\text{CWT}} = D_{\text{HAWT}} \text{Cosec } \phi = 46.7$ m. All the turbines were of the constant speed type with a speed of 40 rev/min for the HAWT rotors and a corresponding rotor speed of 25.7 rev/min for the CWT machines.

The optimum twist of the twisted HAWT blades was established by repeated use of PROPCODE set-up in such a manner that a local twist was established at each radial station, ie. for each annular stream tube. A description of the details of the process has been given by Brophy [3]. The optimum twist for the half-tapered HAWT blade for the 0.075 solidity rotor ranged from $+26^\circ$ near the root to zero at 70% of the blade radius with a negative value of -2° close to the tip. An attempt was made to establish an optimum pitch angle for the untwisted blades of the CWT machines. It was found that the best compromise pitch angle was zero as selected for the performance comparison. For all rotors the performance of the inner 15% of rotor diameter was ignored this being treated as the blade-root and hub zone.

Figure 5 presents a comparison of the performance of a tilt-regulated CWT of 46.7 m rotor diameter with that of a pitch-regulated HAWT of 30 m diameter employing optimally twisted half-tapered blades typical of those used on many wind turbines. The solidity for both rotor types is 0.1. A maximum output of 400 kW can be achieved by the HAWT unit at a wind speed of 12.2 m/s whereas the CWT machine attains this output at 10.2 m/s at the maximum practical tilt angle, ϕ , of 50° (see Fig. 2(b)). At wind speeds greater than those required to achieve maximum output the HAWT is regulated by pitch adjustment and the CWT by reducing the tilt angle which for a wind speed of 20 m/s will have been reduced to approximately 19° . Figure 6 shows data corresponding to Fig. 5 but for rotor solidities of 0.05. Corresponding results for 0.075 solidity yield performance only slightly inferior, in high winds, to those for 0.1 solidity. These results are illustrated elsewhere [3,13].

Figure 7 and 8 show data corresponding to Fig. 5 and 6, respectively, on the power coefficient versus tip-speed ratio plane where the power coefficients of the CWT turbines are based on the projected areas of the ellipses described by the blade tips. The results for a solidity of 0.075 can be found elsewhere [3,13].

Figure 9 presents, for a CWT of 0.075 solidity, the nominal and wind direction forces, F_y and F_x acting on the rotor for tilt angles, ϕ , ranging from 20° to 50° . The required condition for the rotor not to exert a bending moment on an inclinable tower, such as those depicted in Fig. 2, is that the resultant, T , of F_y and F_x aligns with the tower axis. This condition can easily be shown to be that given by the ratio $F_y/F_x = \cot \phi$. Lines representing the cotangent of the tilt angle have been added to Fig. 9 showing that the only tower bending moments contributed by aerodynamic forces acting on the rotor are negative moments (ie. $F_y/F_x > \cot \phi$) occurring under strong wind conditions. It should be kept in mind that the forces due to gravity acting on the tower and the rotor are not included nor are those due to aerodynamic forces acting directly on the tower. It should be relatively easy to minimise the latter since an inclinable tower yaws to follow the wind direction and can, therefore, be provided with an airfoil cross-section sheath.

Figure 10 shows the power input required to motor the 46.7 m diameter CWT at the steady running speed of 25.7 rev/min. This gives an indication of the power input required if the turbine is set at a tilt angle of zero and a storm protection technique of motoring the rotor is adopted in order to use centrifugal force to, in effect, stiffen, under storm conditions, what would otherwise be, under static conditions, very flexible blades similar to those of gyrocopters and helicopters. Figure 10 also gives an indication of the likely start up power required since a CWT rotor of the type described here will not be self-starting. Judging from wind tunnel experience of the first author with a model gyrocopter rotor it is not likely to be necessary to motor the CWT rotor up to full, synchronous, speed to start the machine. It will not be possible to arrange for the CWT to operate, under severe storm conditions, in a fully self-sustaining manner, without rotor over-speeding, as the tip-speed ratio will fall below the minimum required to maintain rotation. It appears that self-sustaining rotation of a CWT rotor of 0.075 solidity can be maintained under full load at a wind speed of up to about 27 m/s and with the rotor unloaded up to about 37 m/s. Only for wind speeds greater than this will motoring assistance be required.

DISCUSSION

Blade dynamics were omitted from the CIERVACALC code hence the CWT blades were always assumed to operate in a plane normal to the axis of rotor spin. In reality an advancing blade tends to rise, and a retreating blade tends to fall, due to the employment of flap hinges. It was the use of such hinges by Cierva that prevented the transmission of a rolling moment to his autogyro aircraft. The omission of flap hinging influences from CIERVACALC is not expected to make a major difference to CWT performance predictions since, to a first approximation, the lift reduction experienced by advancing blades is compensated by the lift gain of retreating blades. For a typical gyrocopter the rise and fall of the advancing and retreating blades, respectively, appears, typically, to be in the region of 1.5° to 2° with blade coning, due to the general balance of centrifugal and aerodynamic-lift forces, in the region of about 8° . An improvement to CIERVACALC would be to include a blade-dynamics sub-routine. Inputs to this could be generated by means of a preliminary design exercise. It is worth noting that neither PROPCODE nor CIERVACALC included the influence of blade boundary layer centrifuging on rotor performance.

Perceived Advantages

Perceived advantages of CWT machines are the elimination of blade flap-wise bending moments under running conditions with no transfer of bending-moment stresses from one blade to the opposite one as in two-bladed teetering rotors. Also some reduction of blade edge-wise bending moments may also be achievable especially if the blade-root attachment can operate, in part at least, as a lead-lag hinge. The CWT concept not only permits the use of simple, non-twisted, fixed pitch, blades but, when applied in conjunction with a tilting tower, offers the possibility of reducing, dramatically, the generation of tower bending moments due to rotor aerodynamic loads. The use of a CWT configuration can also result in a greater power output than that of a HAWT of similar height and robustness.

The use of a ground-level yaw system, which may employ a friction drive without requiring a large diameter ring-gear, encourages the application of an aerodynamic fairing, around a tilting tower thereby reducing tower drag and also disturbance of the flow approaching the lower, downwind, portion of the rotor. The location of the yaw mechanism and nearly all the remainder of the mechanical and electrical system at ground level simplifies maintenance.

A tilting tower arrangement can also make it possible to lower the rotor to ground level very easily if the wind-site is threatened with severe gales or hurricanes. Usually, with modern weather information, gales and hurricanes are forecast sufficiently far in advance to lower the machine before winds of sufficient strength develop to make such an operation impossible. A lowerable tower should also be of assistance when blade inspections, and blade washing, operations are being carried out.

Perceived Disadvantages

CWT machines make less effective use of the blade area provided than corresponding HAWT units. The geometry of CWT units, particularly those with inclinable towers, creates some operational problems if machines of this kind are used in "wind-wall" type installations. Also the need to motor-start a CWT complicates plant operation. However this requirement is a normal feature of Darrieus turbines.

CONCLUSIONS

The concept of the Cierva wind-turbine (CWT) has been described and predicted performances of CWT and HAWT turbines have been compared. It was concluded, from the preliminary data available, that a CWT:

- a) installed on a tilting tower offers a substantially greater power output, for a prescribed tower bending moment due to rotor aerodynamic loads, than a HAWT,
- b) has a greater power output than a HAWT, of equal hub-height, the rotor diameter of which is the same as, or slightly less than, the minor axis of the ellipse constituting the projection, on a vertical plane, of the sweep of the CWT blade tips,
- c) permits relief of blade flap-wise bending moments,
- d) optimum, or near optimum design, tilt-regulated, rotor has fixed-pitch, non-twisted, blades of uniform airfoil section.

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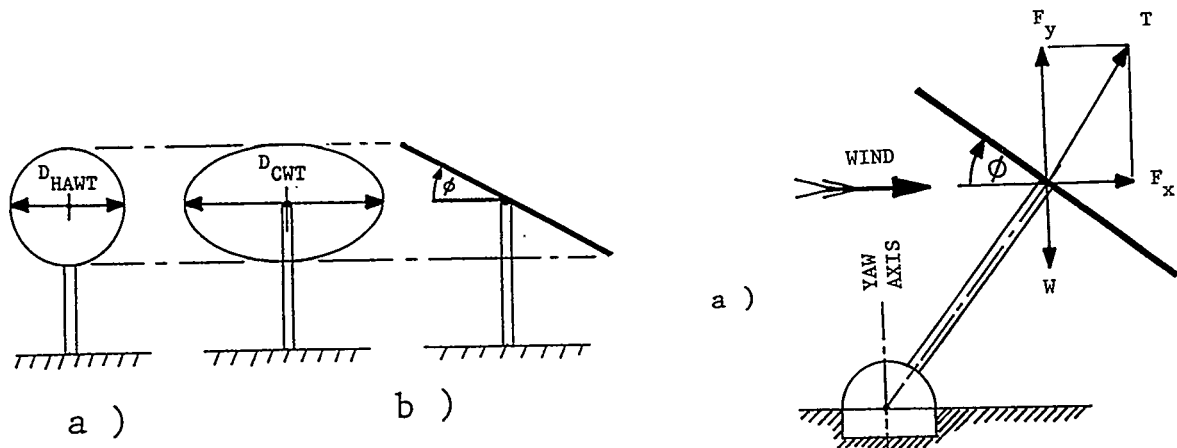


Fig. 1 Projected Area of a Conventional HAWT (a) Compared with that of a CWT (b) when: $D_{CWT} \sin \phi = D_{HAWT}$

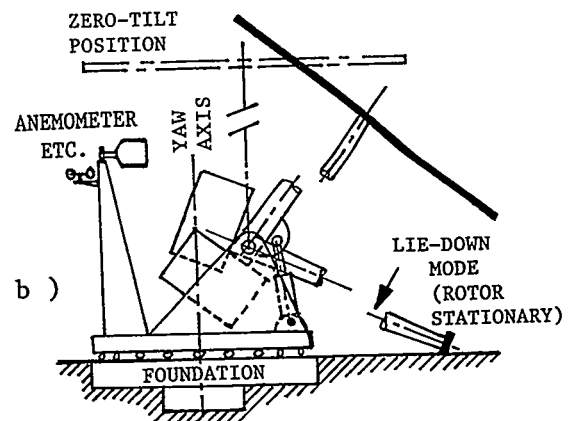


Fig. 2 Tilting Tower CWT
a) Basic Arrangement
b) More Realistic Embodiment

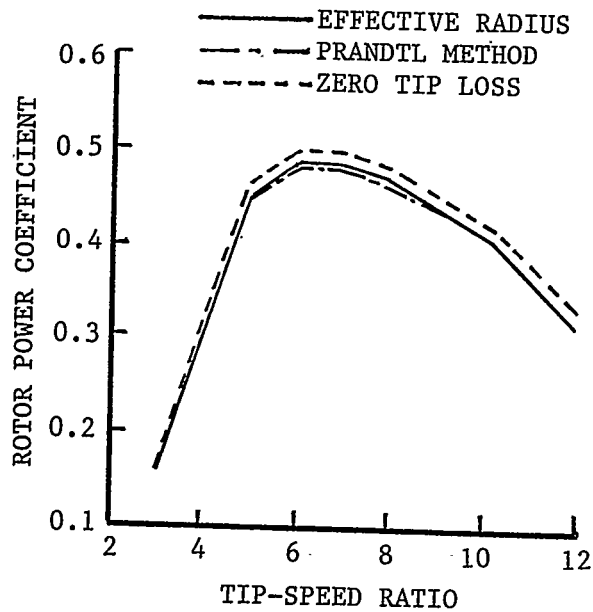


Fig. 3 Comparison of Methods for Accounting for Blade-Tip Losses

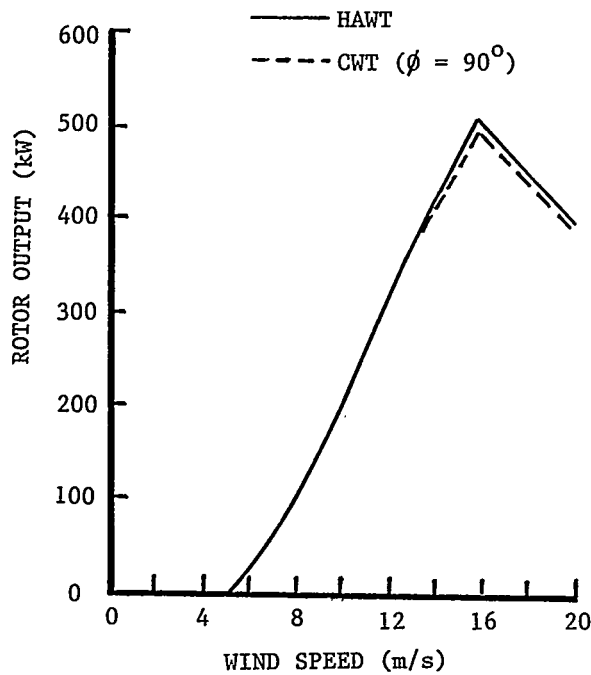


Fig. 4 Comparison of HAWT Performance Predicted Using PROPCODE and CIERVACALC with a Tilt Angle $\phi = 90^\circ$. Rotor Diameters 30 m; Solidity of Each Rotor 0.075

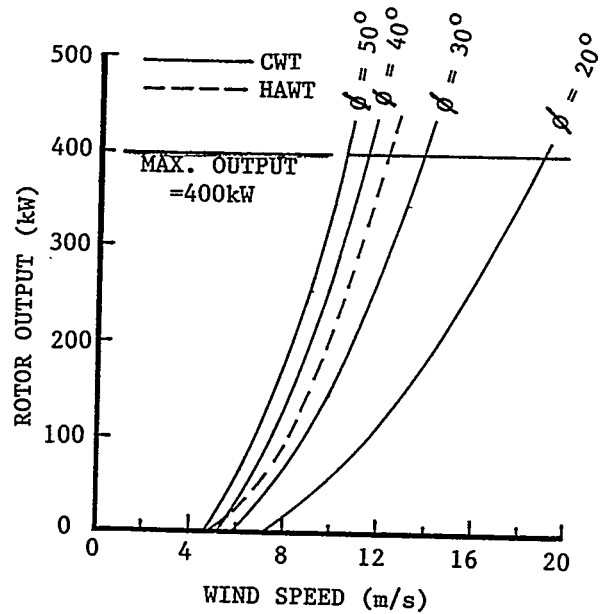


Fig. 5 Power Output versus Wind Speed of a 30 m Diameter HAWT Compared with that of a 46.7 m Diameter CWT ($D_{CWT} = D_{HAWT} \text{Cosec } 40^\circ$). Solidity of Both Turbines = 0.1

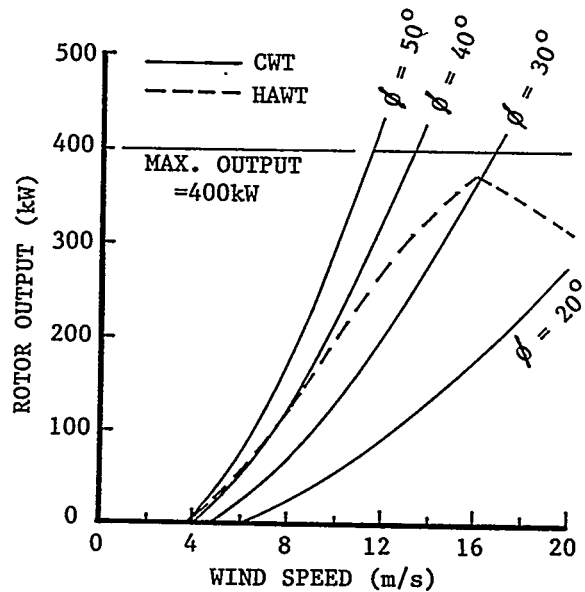


Fig. 6 Corresponding Presentation to Fig. 5 but for Rotor Solidities of 0.05

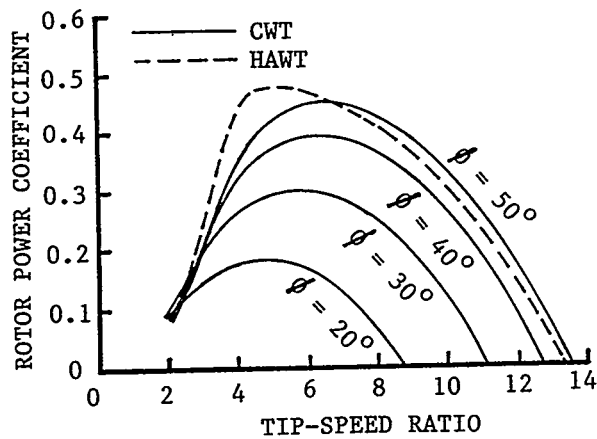


Fig. 7 Power Coefficient versus Tip-Speed Ratio for Turbines of Fig. 5 (Solidities = 0.1)

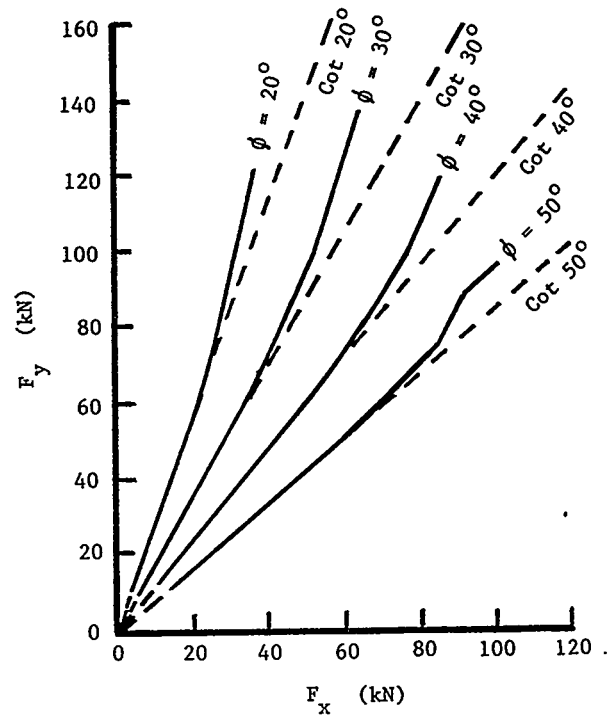


Fig. 9 Aerodynamic Forces Acting on a CWT Rotor of 0.075 Solidity. F_y Acts Vertically Upwards, F_x Acts Horizontally in the Downwind Direction

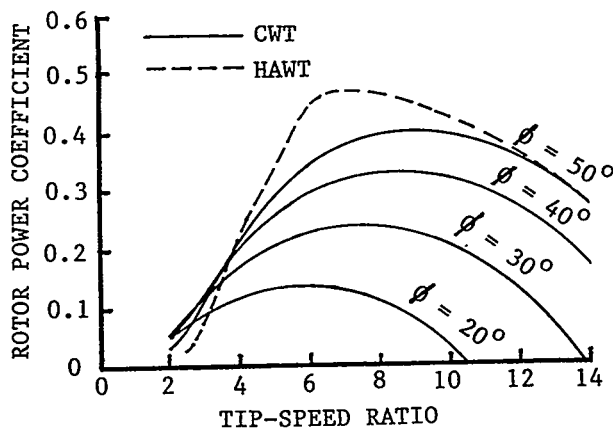


Fig. 8 Power Coefficient versus Tip-Speed Ratio for Turbines of Fig. 6 (Solidities = 0.05)

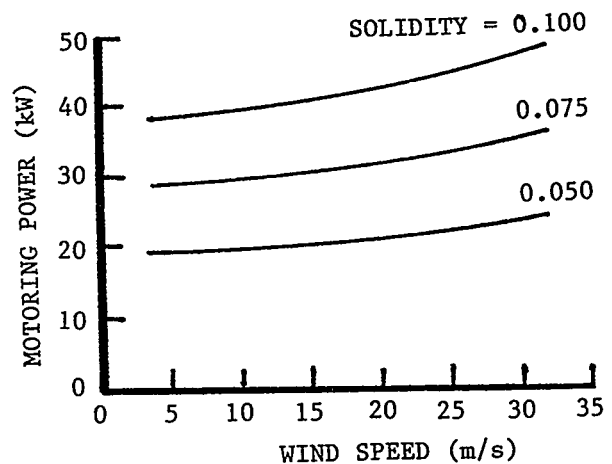


Fig. 10 Power Required to Motor the 46.7 m Diameter CWT Rotors when $\phi = 0^\circ$

A CONCEPT OF WIND-DIESEL HYBRID SYSTEMS FOR THE ELECTRIFICATION OF SMALL RURAL COMMUNITIES IN BRAZIL

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ABSTRACT

This work presents the concept of a wind-diesel hybrid system for the electrification of a small rural community in the Northern Region of Brazil, which can be used in many other places with similar characteristics. The system consists of two small diesel units and two wind turbines, one of which was designed and developed as a prototype with the purpose of gaining some insight in the field of wind turbine technology. Some considerations about small communities of the Northern Region of Brazil, and about electrification concepts are also made.

INTRODUCTION

One of the biggest problems of small rural communities in Brazil, specially in the Northern and Northeastern Regions, is the lack of electricity, and the almost unhopeful probability of being supplied by the local utilities. Considering this situation, studies were started to develop a concept of a wind-diesel hybrid system which could provide the necessary electrical energy to enhance the social and economic status of the population, and be used as a model for isolated communities with similar characteristics as the one chosen.

SMALL RURAL COMMUNITIES IN THE AMAZON REGION

The solution for the electricity supply for the populations in the Amazon Region has always been a matter of great controversy among researchers and institutions dealing with energy. Lately, this question has become crucial, due to the demands, which were created in the Region, and to the importance given to environmental problems, which were seldom considered before.

The energy model used until now has been based on the big hydroelectric plants, which supply mainly the big demands, represented by the large cities and local industries, besides exportation to the Northeastern and Southeastern Regions.

The small population centers, represented by the rural communities, and which are predominant in the occupation model of the region, are not supplied by these large plants, due to the economic unfeasibility of the implantation of transmission lines and substations to attend these low demands.

The needs of these small population centers are basically the supply of drink water (pumping and treatment), irrigation, communication, operation of small processing units for land products, lighting, and the maintenance of a medical office, a school, a community center, besides amusement.

The implementation of a simple electrification system is almost always sufficient to provide for these basic needs. It is also important, that such systems introduce some kind of economic activity, to provide a means for its operation and maintenance on a self-sustained basis.

The community of Praia Grande, at the Marajó Island, was selected due to the following reasons:

Location at nine kilometers from the county capital, at the Marajó Bay, with favorable wind potential (annual mean of about 5 m/s, with speeds up to 10 m/s);

Similar geographical characteristics to other communities on the island;

Proximity of the State Capital (44 km), favoring the transport of people and equipment, as well as the demonstration effect;

Size of the community, composed of 25 houses, school, community center, population around 130 inhabitants, which represents a typical occupation model for small rural communities in the Northern Region of Brazil;

Presents a good communal organization, being already assisted by a drink water system, which uses a windmill for the water pumping and PV panels for the bacteriological treatment through electrolysis;

Has a small infra-structure for the extraction and commercialization of coconut fiber, which needs electricity for a probable future expansion.

Moreover, it is not supplied and has no short term perspective to be supplied by the local utility by conventional means. Considering also the fact that it has a tourist potential, it is expected that the project can bring good results concerning the demonstration effect and the replication to other regions with similar characteristics.

SYSTEM CHARACTERISTICS

After the studies of load demand and wind potential, which are shown in figures 1 and 2, a wind turbine of 15 kW was designed, which, integrated to two diesel generators of 7.5 kVA each, composes a hybrid system, capable of supplying the electrical energy needs of the community, including a forecast of future expansion.

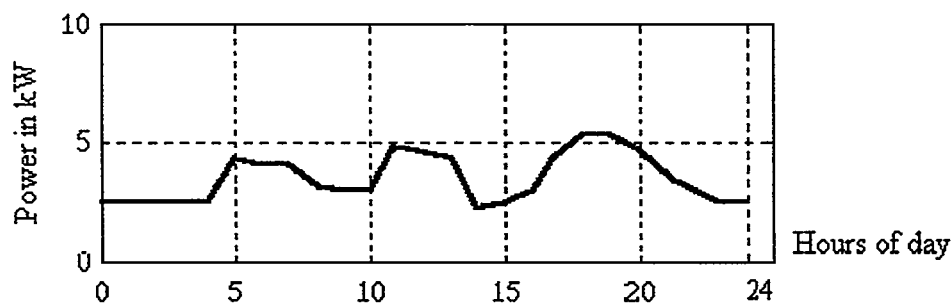


Figure 1 - Demand curve

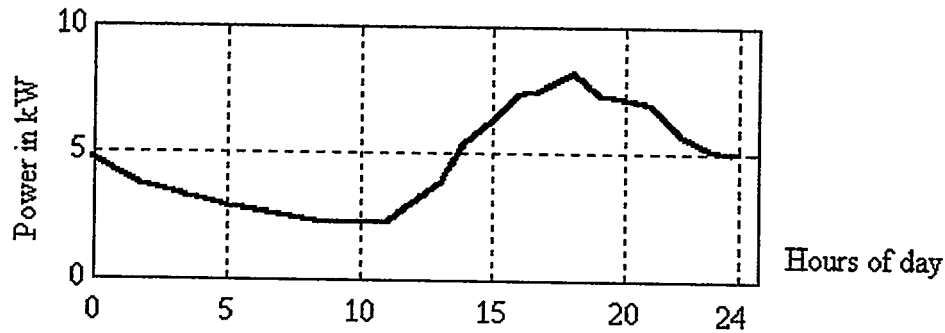


Figure 2 - Wind power curve

The wind turbine was designed by the university staff and built with local technology.

The system consists of the following components:

Wind turbine - 3-blade-rotor with 12 meters diameter, using a modified NACA 23021 profile;^[1,2]

Nacelle - mounted on ball bearings and positioned by a vane system, and containing a gear box and the electrical generator;

Tower - 15-meter-high with self-sustained structure;

Electrical generator - three phase induction motor, four poles, 220/380/440 V, 20 HP, self-excited by a capacitor bank of 7,5 kVAr, with a three-phase diode rectifier;^[3]

Battery bank - 18 lead-acid batteries, 12 V/150 Ah;

Static inverter - 15 kW, 220 Vdc/120 Vac, single-phase 60 Hz;

Distribution grid - low voltage (120 V), extension of 1.6 km, distributed in two branches of 700 m and 900 m, with wood poles.

A block diagram of the wind turbine generator is shown in figure 3, and the circuit of the rectifier in figure 4.

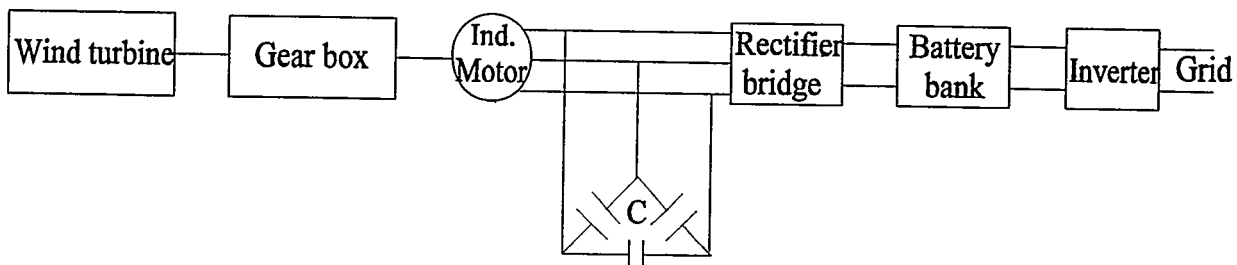


Figure 3 - Block diagram of the wind turbine generator

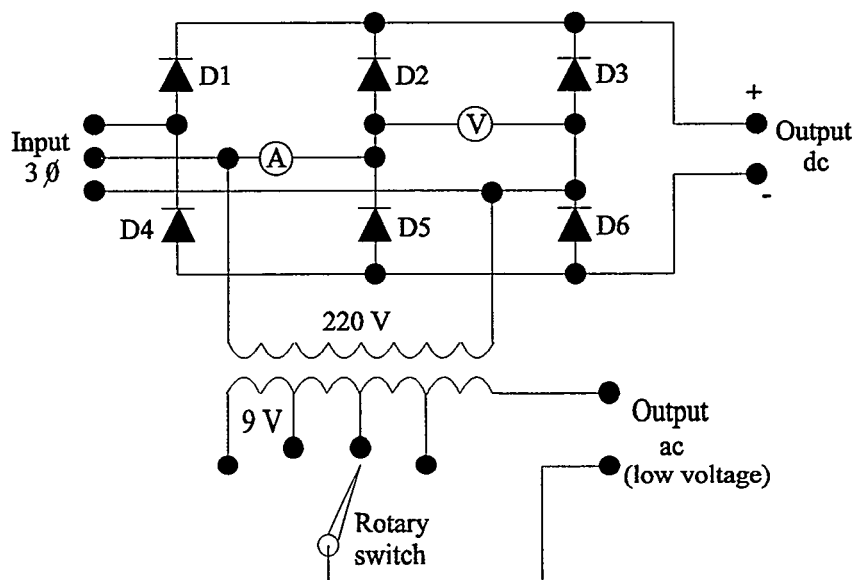


Figure 4 - Diode rectifier

The wind turbine generator, as shown in figure 3, is connected to the grid together with the two diesel generators through an ac-bus, which is controlled and synchronized manually according to the circuit of figure 5.^[4,5]

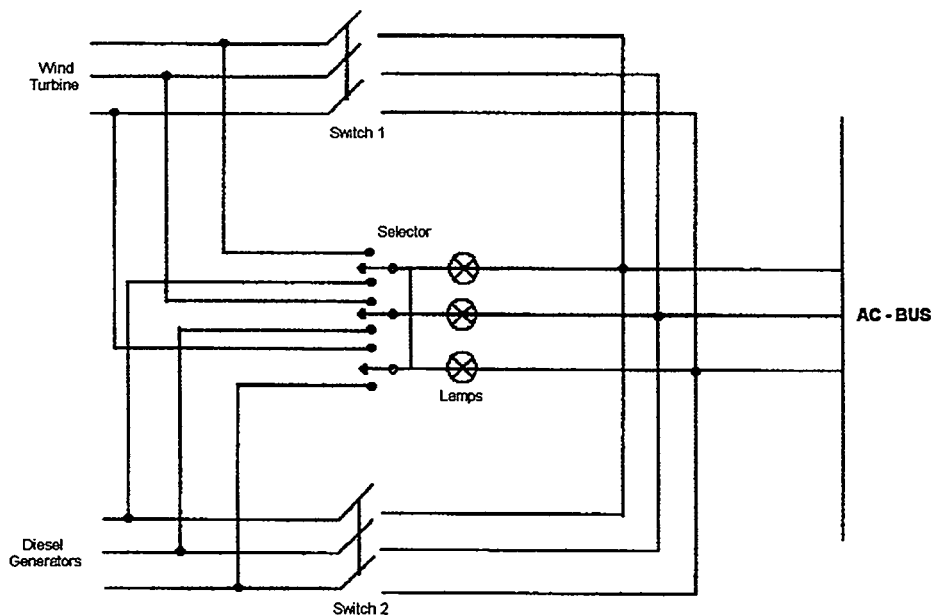


Figure 5 - Manual synchronization of the different sources

RESULTS

The system, as described in the previous topic, was implemented and mounted in the laboratory, with the exception of the rotor blades.

Several tests concerning the operation of the induction motor with its self-excitation, the rectification and charging of the batteries, the dc-ac inversion, and the simulation of variable wind speeds with a dc-motor coupled to the induction motor were completed and published.

The energy coordination of the whole system was simulated in a computer^[4,5], and tested with resistive and inductive loads, simulated by 36 100 W-lamps and a 1 HP-motor.

The systems is now being assembled at its final place, and it was decided to include a commercially available wind turbine of 10 kW to study and compare the behaviors of both wind machines. This new turbine will also be connected to the ac-bus.

FURTHER WORK

Further studies of the wind potential at the locality are planned, with the installation of an automatic measurement system, including solar radiation as well. This data will be used to monitor the operation of the system, specially the wind turbines.

The coordinated operation will also be monitored, including the percentage of the individual generation sources, their operation cycles, on-off switching criteria, and the mechanical and electrical limits, together with possible failures.

With respect to manual parts of the operation, two members of the community are being trained to operate the system and to perform simple maintenance routines.

The other members of the community are also being educated through pamphlets and speeches to make good use of the available energy, considering the fact that the energy offer is limited and, for this reason, must have a good social and economic destination.

A social and economic study of the situation of each household is also being carried out^[6], in order to find out which impacts the electrification can cause in the community. As social and economic indicators, the following items were chosen: family income; expenses with energy and transportation; domestic facilities (TV, refrigerator, radio, etc.); school attendance; fixed and floating population; economic activities; communal services (school, medical office, etc.); amusement activities; medical assistance.

CONCLUSIONS

A concept of wind-diesel hybrid generation system was proposed to supply small villages in the Northern Region of Brazil. Part of this system, namely the wind turbine generator with its components, was developed and constructed using local technology. A concept of coordinated operation was developed and tested, showing good preliminary results.

As a second phase, the system is being assembled at its final operating location, and further studies are being planned, in order to monitor its overall performance and its impacts on the community life.

With the experience gained in this and other similar projects, it has been made clear that to make the utilization of renewable energies possible, a series of economic, social, and environmental aspects must be taken into account, besides considering the revision of certain well-established concepts.

The following points are considered as extremely important:

The generated energy must be adequate to the basic needs and the specific uses of the localities, trying to avoid misuse.

The choice of energy sources must be made according to the local characteristics, using the most direct possible type of conversion.

The systems must be simplified to allow its implantation, maintenance, and operation by the members of the communities, with little technical supervision.

Well known solutions or its adequacy to local realities must be used whenever possible, considering as important points the environmental preservation, and the reduction of costs.

The technical regulations for the generation and distribution, which are today basically concerned to the big cities, must be reviewed and altered to allow the reduction of costs of implantation, operation, and maintenance, maintaining the reliability and the safety of the system.

The concept of reliability, which is today understood as round-the-clock, should be rethought, considering mainly the communal uses.

The new systems should be competitive regarding the conventional, for the reasons of isolation, resource scarcity, pollution, energy independence, or simply for lower costs.

The technical, economic, and social problems related to the use of renewable energy sources are inseparable.

The authors believe that the most viable solution for the problem of electrification of small communities is the decentralization of the generation using as many energy sources as possible, and the diesel simply as a back-up to account for reliability.

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PERFORMANCE OF A 10 KILOWATT WIND-ELECTRIC WATER PUMPING SYSTEM FOR IRRIGATING CROPS

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ABSTRACT

A 10kW wind-electric water pumping system was tested for field crop irrigation at pumping depths from 50 to 120 m. The wind turbine for this system used a permanent magnet alternator that powered off-the-shelf submersible motors and pumps without the use of an inverter. Pumping performance was determined at the USDA-Agricultural Research Service (ARS), Wind Energy Laboratory in Bushland, TX for the 10kW wind turbine using a pressure valve and a pressure tank to simulate different pumping depths. Pumping performance was measured for two 10kW wind turbines of the same type at farms near the cities of Garden City, TX and Stiles, TX. The pumping performance data collected at these actual wells compared favorably with the data collected at the USDA-ARS, Wind Energy Laboratory. If utility generated electricity was accessible, payback on the wind turbine depended on the cost of utility generated electricity and the transmission line extension cost.

INTRODUCTION

Wind power is used throughout the world to pump water for domestic and livestock use. The intermittent nature of the wind is not as big a problem for pumping water as with electric power generation since water can be stored on windy days and used later on days when the wind is calm. When one generates electrical power from the wind for uses other than pumping water, significant power can be lost storing it in batteries for later use. Also, most electrical applications require constant voltage and frequency electricity which requires the use of an inverter when a wind turbine with a permanent magnet alternator is used. A way was developed at the USDA-ARS to directly couple a permanent magnet alternator wind turbine to a submersible motor without using an inverter which resulted in significant cost savings and an improvement in efficiency for the wind-electric water pumping system (Clark, 1989). Mechanical windmills are currently being used all over the world to pump water in daily water volumes of 1000 to 20,000 l/d. Some farmers and ranchers are replacing their aging windmills with wind-electric and solar water pumping systems. However, for daily water volumes greater than 20,000 l/d at well depths greater than 50m, the only stand-alone (no utility intertie) option, besides using a diesel generator, is to use a 10kW or larger wind turbine with a permanent magnet alternator. Although utility electricity is fairly abundant and cheap in the Great Plains at the present time, as deregulation continues and a leveling of the prices occurs across the country, the price of utility supplied electricity to remote locations will probably increase significantly.

The Bergey Windpower¹ Excel-PD wind turbine has been used for pumping water for small off-the-grid villages for several years. Research on this wind turbine at the USDA-ARS in Bushland was begun in 1988, and it was identified as a good candidate for supplying water to small villages. The system cost is reduced significantly by not using an inverter, but directly connecting the variable voltage, variable-frequency, 3 ϕ , AC electricity from the wind turbine to an off-the-shelf submersible motor and centrifugal pump. An inverter for converting the wind turbine electricity to 230V, 60Hz, 3 ϕ , AC is avoided by using a controller and adding capacitance in parallel with the inductive motor to improve the power factor.

In 1989 the USDA-ARS in Bushland made a proposal for using a wind-electric water pumping system for small scale irrigation in West Texas. This proposal was approved by the Texas Governors Energy Office in Dec. 1990. When a new governor came into office in 1991, the proposal was disapproved. USDA-ARS personnel at Bushland went ahead and measured hourly wind speeds in the Garden City area from 4/1/91 until 3/31/92. Then in Sept. 1994 the proposal was approved again by the Texas Sustainable Energy Council. The installation of the two Bergey Excel-PD wind turbines was performed by USDA-ARS personnel on July 26, 1995 on two 32.8m Rohn¹ (model 45g) towers at two farms, one located near Garden City, TX and the other near Stiles, TX. The two water pumping systems were instrumented in the spring of 1996 and data has been collected since that time.

RESULTS

Pumping depth or head is simulated on the wind-electric water pumping systems at Bushland by using a pressure valve in combination with a pressure tank. The pressure is set in the water pumping system by connecting the motor and pump to utility power and adjusting the pressure valve until the desired pressure is obtained. When the motor and pump are connected to the wind turbine, the pressure varies with wind speed. In order to determine the pumping performance at a certain well pumping depth, two sets of data at different pressures have to be collected which bracket the well pumping depth. The motors used in Bushland, Garden City, and Stiles were Franklin Electric¹ 5.6kW, 230V, 3 ϕ , AC submersible motors. The motors used in Bushland and Stiles were 10cm in diameter, and the one used in Garden City was 15cm in diameter. Grundfos¹ 3.7kW 15-stage centrifugal pumps were used at all three locations.

Garden City (Site 1)

Figure 1 shows the average pumping depth of the well at Garden City from 6/26/96 until 7/23/96 as a function of wind speed. Two pressure data sets (414 kPa and 690 kPa) were selected from the test data collected at Bushland which would bracket the data collected at Garden City and these data are also shown in Figure 1. Figure 2 shows the flow rate measured for the two sets of pressure data gathered at Bushland(symbols). Since the pumping depth for the Garden City well varied between 50 and 60 m due to well draw down(see Figure 1), the flow rate data was linearly interpolated according to the pumping depth in order to predict the flow rate at constant pumping depths of 50 and 60 m (lines). Figure 3 shows a comparison of the predicted flow rate (based on the Bushland experimental data) to the actual flow rate measured for the well at Garden City. The predicted flow rate compares very well to the actual flow rate up to a wind speed of about 9 m/s. For a wind speed range of 9 m/s to 13 m/s the actual flow rate exceeds the predicted flow rate. In Figure 3, the average flow rate is shown when considering only ON data (i.e. only data when the pump is pumping water) and ON + OFF data (i.e. all the data whether pumping water or not). The difference in flow rates for wind speeds of 10 m/s and above can be explained by higher wind speeds causing the wind turbine to lose synchronization with the motor. This is why the flow rate for the ON+OFF data

¹ The mention of trade or manufacture names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA - Agricultural Research Service.

is below the flow rate for the ON data in this wind speed range. For a more detailed explanation of the effect of synchronization loss, see (Vick, 1996). Figure 4 shows how the hourly wind speed distributions differed between the Bushland data, and the Garden City data (i.e. more high wind speed data was collected in Bushland).

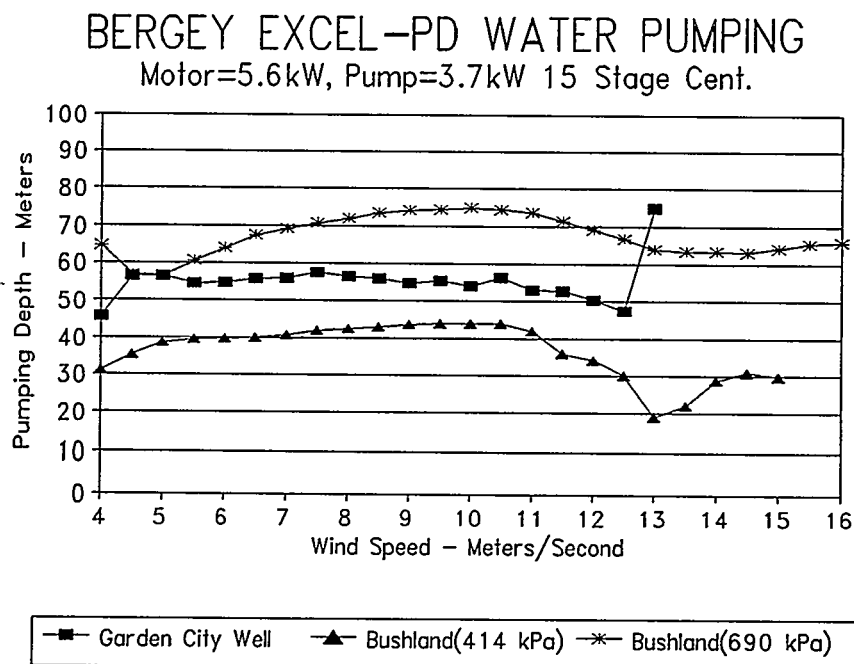


FIGURE 1. MEASURED PUMPING DEPTH FOR GARDEN CITY AND DATA COLLECTED AT TWO PRESSURES AT BUSHLAND.

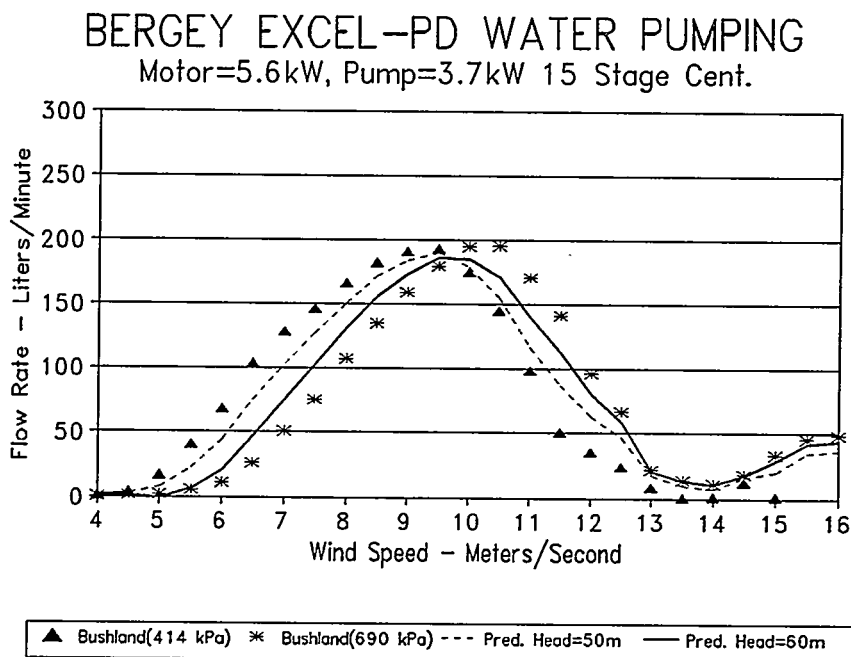


FIGURE 2. MEASURED FLOW RATES AT TWO PRESSURES AT BUSHLAND AND TWO PREDICTED FLOW RATES AT 50 AND 60 METER HEADS.

BERGEY EXCEL-PD WATER PUMPING

Motor=5.6kW, Pump=3.7kW 15-Stage Cent.

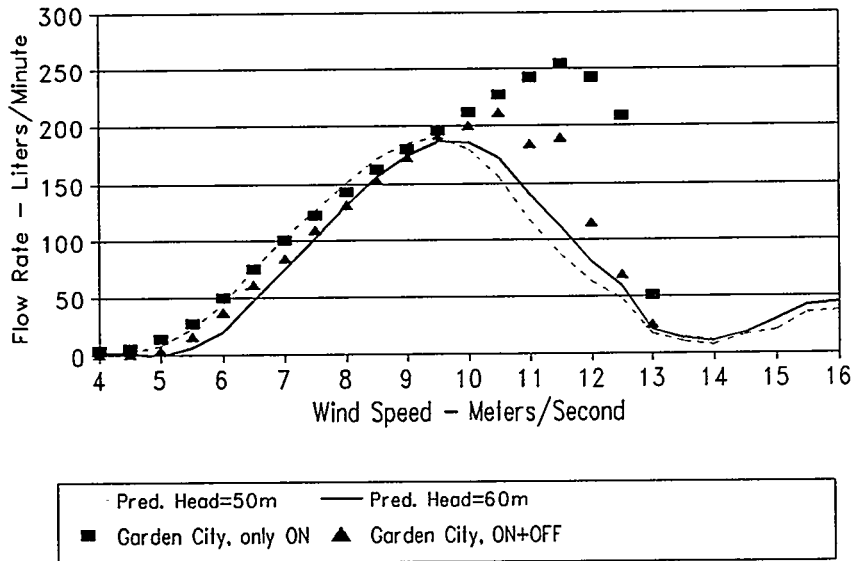


FIGURE 3. PREDICTED FLOW RATES AT 50 AND 60 METERS AND MEASURED FLOW RATES AT GARDEN CITY FOR BOTH "ON" AND "ON+OFF" DATA.

BERGEY EXCEL-PD WATER PUMPING

Motor=5.6kW, Pump=3.7kW 15 Stage Cent.

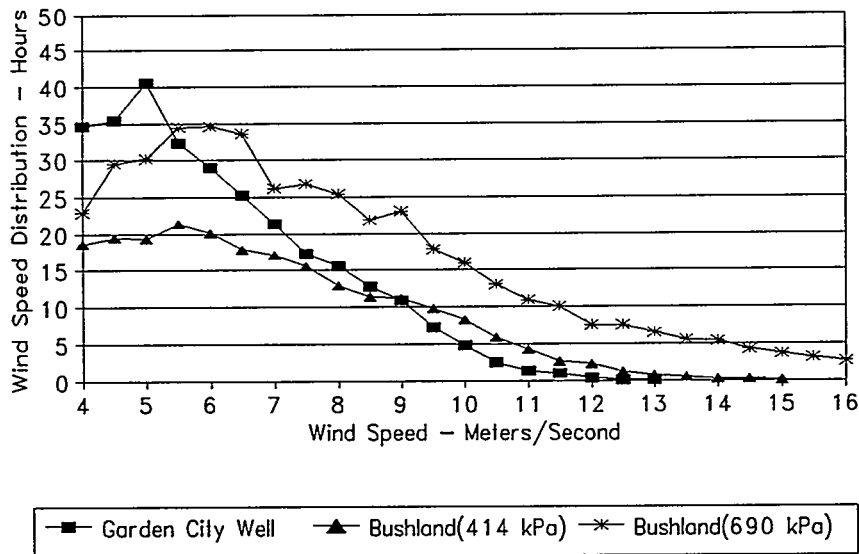


FIGURE 4. GARDEN CITY & BUSHLAND WIND SPEED DISTRIBUTIONS.

Stiles (Site 2)

Figure 5 shows the average pumping depth of the Stiles well as a function of windspeed over the period 4/24/96 to 8/4/96. Also shown in Figure 5 is the average pumping depth of two sets of data which were gathered over two pressure ranges. Again, the Bushland data were set at 965 kPa(140 psig) and 1207 kPa(175 psig) using utility power, but the pressure varied with wind speed which meant the simulated

pumping depth also varied. The Bushland simulated pumping depth data bracketed the Stiles data which varied in pumping depth from 85m to 125m. Figure 6 shows the flow rate gathered in the two pressure data sets (symbols) and the predicted flow rates for 80m, 100m, and 120m (lines).

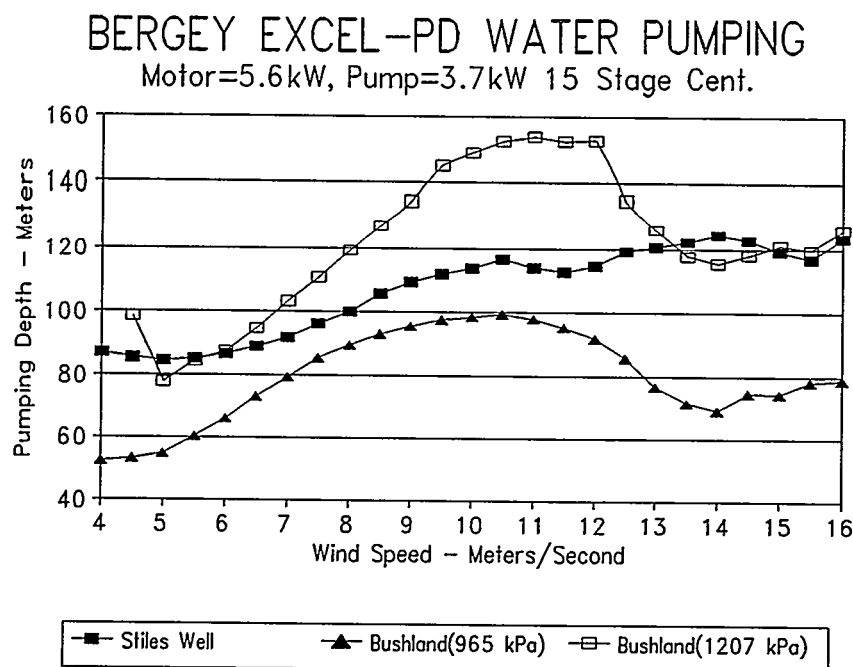


FIGURE 5. MEASURED PUMPING DEPTH AT STILES AND DATA COLLECTED AT TWO DIFFERENT PRESSURES AT BUSHLAND

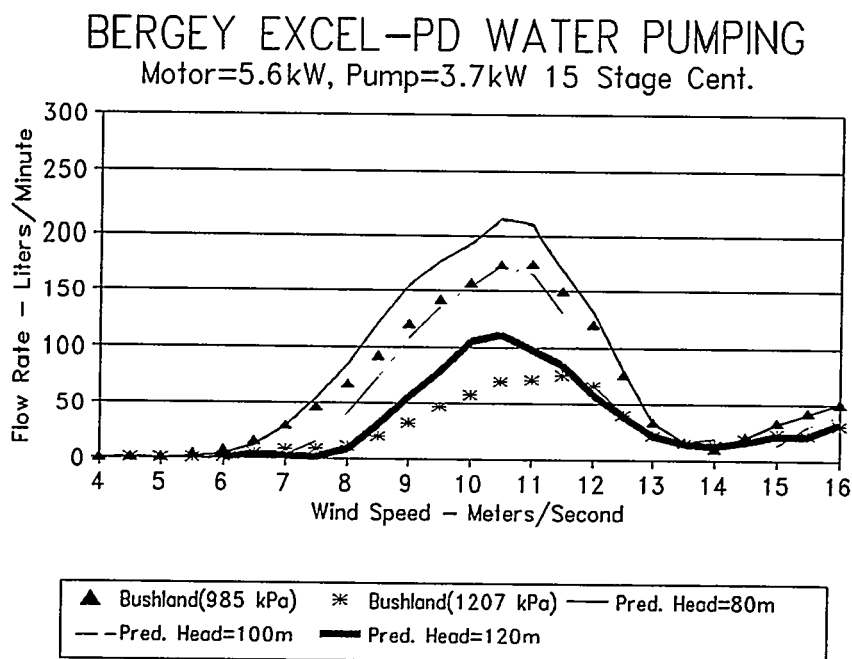


FIGURE 6. MEASURED FLOW RATES AT TWO PRESSURES & PREDICTED FLOW RATES AT HEADS OF 80, 100, & 120 METERS.

Figure 7 shows the predicted flow rates for 80m, 100m, and 120m pumping depths (based on Bushland data) and the flow rate measured at the Stiles well. As with the Garden City well, both “ON” and “ON + OFF” average flow rates are shown in Figure 7. Again, predicted and measured flow rates are generally in agreement.

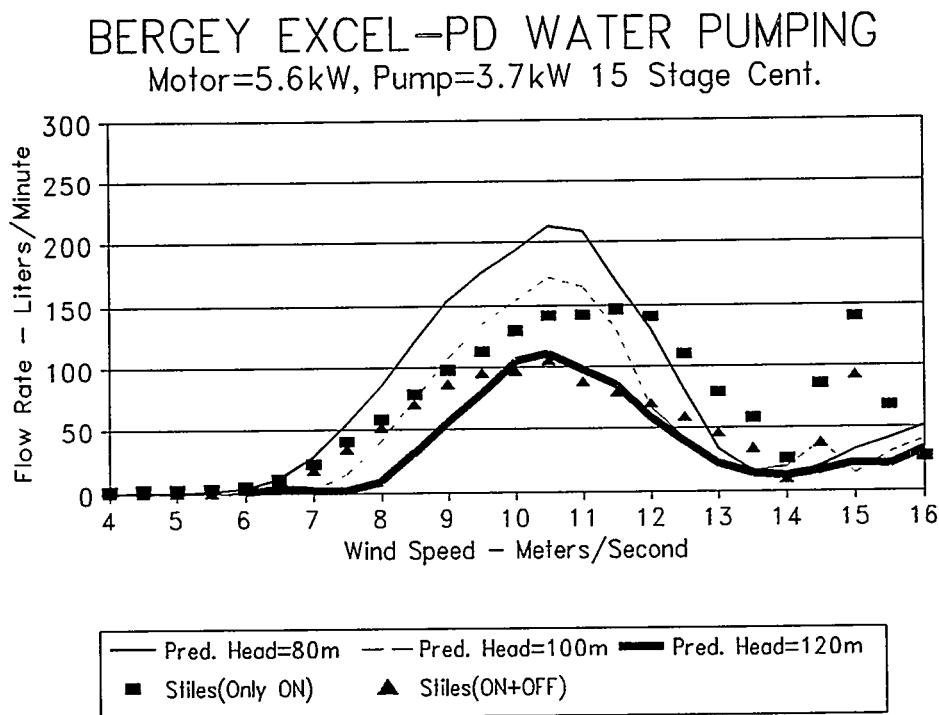


FIGURE 7. PREDICTED FLOW RATES AT 80, 100, AND 120 METERS, AND MEASURED FLOW RATES AT STILES FOR BOTH “ON” AND “ON+OFF” DATA.

Daily Water Volume for the Bergey Excel-PD

Since the predicted flow rate based on the Bushland data appears to be correct, an estimation of the daily water volume for the Garden City area should be possible. Figure 8 shows the daily water volume for the Bergey Excel-PD when using an hourly distribution of wind speeds collected at Garden City at a 24.4m(80 ft) height from 4/1/91 to 3/31/92. The average wind speed that was measured during this time was 6.32 m/s. Using the Bushland flow rate data and the one year’s worth of wind data collected at Garden City, the predicted annual average daily water volume for the 60m head was 80.2 m³/d while for the 100m head it was 35.7 m³/d. Noticeably very little water would be pumped in August for the 100m head.

Field Experience for the Bergey Excel-PD in Irrigation

Although flow rate prediction at the wind laboratory in Bushland is important for estimating daily water volume at a certain location, several unique problems were identified when the Bergey Excel-PD’s were field tested. One difficulty was in troubleshooting the field wind turbines when no water was being pumped when it should have been. In the laboratory we can switch the motor/pump from the wind turbine to the utility by using a double-throw switch. By doing this we can determine if the problem is with the wind turbine/controller or the motor/pump. Although there was utility electricity at both field sites, it was 480V, 3 ϕ , AC and the motors used for the Bergey Excel-PD turbine are 230V, 3 ϕ AC. One way to help in trouble-

shooting would have been to buy two motors and two pumps and have one of the motor/pump combinations in a barrel or tank of water close to the wind turbine to determine if the wind turbine/controller was operating properly. Of course if the wind turbine had been designed to provide 3 ϕ , 480V electricity which is typical of larger irrigation motors in the Texas High Plains, this would have helped in trouble-shooting problems in the field.

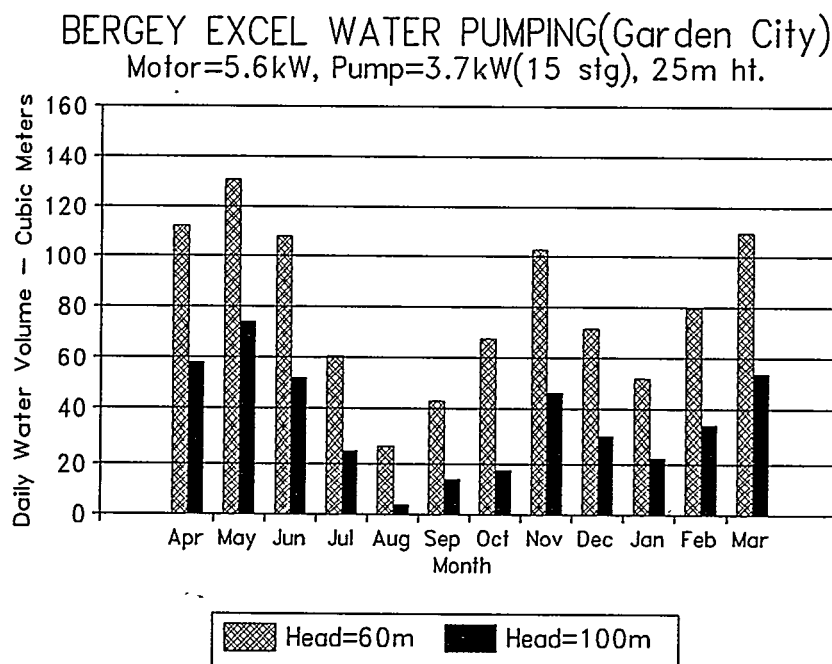


FIGURE 8. DAILY WATER VOLUME PREDICTION FOR WATER WELLS AT GARDEN CITY AND STILES.

Another problem with using a wind turbine for irrigation was uneven watering of the field. The farmer knew when he used the utility how many inches of water he was getting on certain rows. The variability of the wind resulted in the farmer being unsure of how much water the rows were getting. One possible solution for the Garden City well suggested by Warren Multer (Texas Ag Extension Service) was to have the wind turbine pump water into a 75.7 m³ oil field tank, then use gravity feed or a booster pump to pump the water into the field once the tank was full.

Economic Analysis for Using Bergey Excel-PD for Irrigation

Figure 9 shows the payback that would be expected as a function of what the cost of electricity would have been if the wind turbine had not been used. Only the payback for the 60m pumping depth is shown because the payback is similar for a 100m head. Assumptions used in producing this graph were a 95% availability for the wind turbine, a maintenance cost of \$100/year, and a cost of \$26,825 for the wind turbine, tower, foundation, guy cables, crane cost, backhoe, and electrical cable. The lifetime of this wind turbine is estimated to be 20 years. If the cost of the electricity is less than \$0.10/kWhr, buying this wind turbine would not be economical. Since the present cost of utility electricity in the Garden City area is \$.065/kWhr, and if utility electricity is available (we are defining available as less than 100m), buying this wind turbine would not be economical. If utility transmission lines have to be extended, it may be economical to consider buying this wind turbine. The local electric cooperative in the Garden City area charges \$7500 for each 1km(0.6 miles) extension of the 3-phase transmission lines. So in Figure 9, the payback is also estimated for a 1 and 2 km

transmission line extension. Of course if the transmission lines have to be extended over 4 km, it is obvious that the wind turbine is economical no matter what the cost of the utility electricity is. Another option for a farmer without utility access, is to use a diesel generator. The cost of using a diesel generator to supply the power is estimated to be about \$0.20/kWhr which again indicates buying this wind turbine would be a good investment. Profits from cotton production are often doubled or tripled by the addition of a single irrigation, therefore, farmers prefer to apply as much water as allowed by the wells without excessive drawdown. Drawdown is evident in the data shown for the water well near Stiles, TX(see Figure 5), since well depth varied from 85m to 125m as the windspeed increased. Current practice for irrigating cotton in West Texas with utility supplied electricity is to irrigate from February until September. Since the Garden City well average flow rate provided by this wind turbine is less than half of that provided by utility power, a decrease in cotton yield would be likely. If utility electricity is available and considering the current cost of utility electricity, the cost of the wind turbine will have to decrease by at least a factor of 2 to make the wind turbine cost effective.

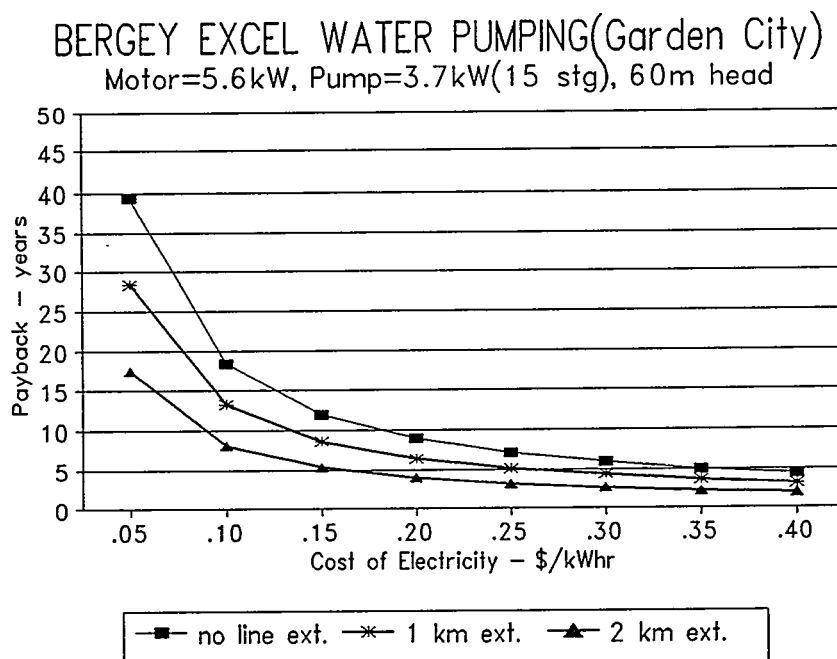


FIGURE 9. CALCULATED PAYBACK OF BERGEY EXCEL-PD AS A FUNCTION OF THE COST OF ELECTRICITY AND HOW FAR TRANSMISSION LINES HAVE TO BE EXTENDED.

CONCLUSIONS

Bergey Excel-PD water pumping data were collected experimentally at Bushland, TX and compared to field data in which Bergey Excel-PD's were pumping water from actual water wells in Garden City, TX and Stiles, TX. The experimental and field data that were both collected using the same type wind turbine, controller, motor, and pump. The predicted flow rates at Bushland compared favorably to the measured flow rates at Garden City (average 55m pumping depth) and Stiles(average 100m pumping depth). Since predicted and measured flow rates correlated so well, using the predicted flow rates together with some measured wind data over a one year period was used to predict daily water volumes for each month. Using the 15-stage pump for pumping water at a 60m head appeared to be satisfactory, but it appears obvious that a pump with more

stages is needed for the 100m head. At the current price of utility electricity in the Garden City area, it is not economically feasible to use the Bergey Excel-PD for irrigation if 3-phase utility electricity is available. If 3-phase utility electricity is not available, the Bergey-PD wind turbine may be economical depending on how far the transmission lines have to be extended or how expensive the diesel generated electricity is.

ACKNOWLEDGMENTS

We would like to express our thanks to the following people: Ron Davis(USDA-ARS) for installing the portable meteorological tower and recording one year of wind speed data in the Garden City, TX area; Ron Davis and Eric Eggleston (USDA-ARS), and Mike Bayless (formerly with USDA-ARS) for helping to install the Bergey Excel-PD's in Garden City, TX and Stiles TX; Joe Henggeler (formerly with Texas Ag Extension Service) and Warren Multer (Texas Ag Extension Service) for helping with the instrumentation, data retrieval, and maintenance of the Bergey Excel-PD water pumping systems; Peter Huebner and Mike Bergey of Bergey Windpower for their quick attention and response to wind turbine and controller related problems.; the farmers Joe Schwartz and Robert Michalewicz for agreeing to let us use their land to field test the Bergey Excel-PD for irrigation.

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WIND RESOURCE ASSESSMENT: A THREE YEAR EXPERIENCE

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ABSTRACT

This paper presents the results of data collected from three different sites located in the central, northern and eastern region of Saudi Arabia. Each site is geographically and climatologically different from other. Statistical moments and frequency distribution were generated for the wind speed and direction parameters to analyse the wind energy characteristics and its availability. The results of these statistical operations present the wind power and energy density estimates of the three sites. The data analysis presented a prospect of wind energy conversion and utilization. The annual extractable energy density is 488, 890, 599 kWh/m² for the central, northern and eastern sites respectively. Also, the paper demonstrates the lessons learned from operating wind assessment stations installed in remote areas having different environmental characteristics.

INTRODUCTION

More than 70% of the world's energy consumption is greatly dependent on fossil fuel as its source. However, it is exhaustible and is now used very rapidly due to the continuous rise of the world's population. Soon, this energy source will be depleted. For this reason, research and development had been focused to renewable energy technology having abundant and inexhaustible sources. Wind has been proven as a reliable alternative source and wind energy technology has reached that point that it can compete with the conventional power generating machinery. ERI- KACST, a governmental entity, is mainly engaged in renewable energy research. Since wind is inexhaustible and is a secondary form of solar energy, ERI-KACST has pursued to assess the wind energy potential of the country (Alawaji, 1996). Five sites were selected to geographically represent the country; one each from the north, south, east, west and central region. The sites were chosen from the Saudi Arabian Wind Energy Atlas. This Atlas was generated by a research team from KACST and from the King Fahad University of Petroleum and Minerals (KFUPM) under the sponsorship of the Saudi Arabia - United States Joint Program for Cooperation in the field of Solar Energy (SOLERAS) (Al-Ansari, et al., 1986).

WIND STATION SITES AND HARDWARE

The Wind Energy Project is comprised of 5 monitoring stations which are located in various parts of Saudi Arabia. Details of the geography of the three sites selected for the subject of this paper are listed in Table 1. A wind station is generally comprised of a tower, sensors and a data acquisition system (DAS). The tower is a steel tube having a length of 40 m. It consists of 14 lengths of 3 meter, 15.24 cm diameter tubes inserted to one another. Wind speed sensors are installed at heights 40, 30 and 20 m. Each height has two sensors. In case one sensor fails, the other still operates, thus, ensuring continuous data collection. Wind direction sensors are also installed at two heights, 30 and 40 m. Two sensors are installed for the reason stated above. Other meteorological sensors to measure global insolation, ambient temperature, relative humidity and barometric pressure are also configured to the wind station.

TABLE 1. WIND STATIONS IN SAUDI ARABIA.

Site	Latitude (deg)	Longitude (deg)	Elevation (m)
Ar-ar	30.8°	41.3°	550
Dhahran	26.1°	50.1°	3
Riyadh	24.6°	42.6°	620

The DAS is a mini computer which can be programmed to have an averaging interval of a minimum of 1 minute to a maximum of 1 hour. Its power supply is a two 6V, 3.8 Ah battery charged by a 10W amorphous silicon PV panel. Its non-volatile storage is a 256 Kb PCMCIA data card. The tower is equipped with an obstruction light installed on top of it. It is powered by a 220 VAC from the utility grid or from a photovoltaic power system.

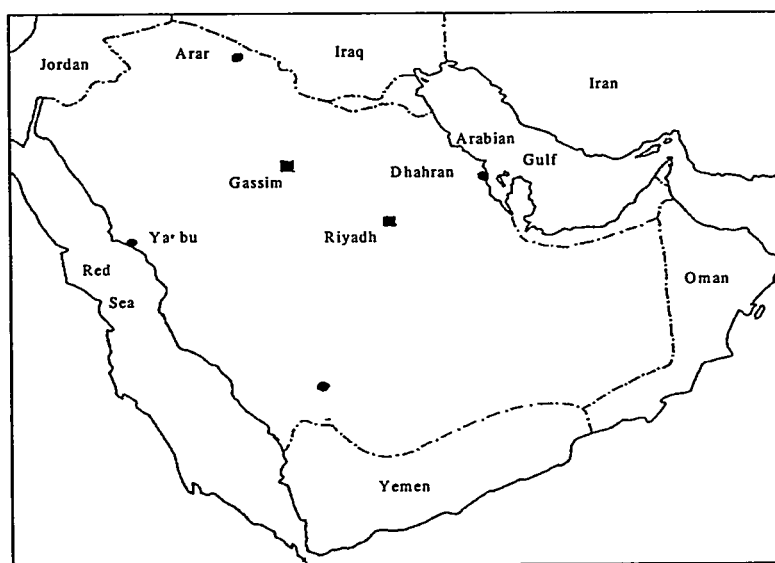


FIGURE 1. MAP OF SAUDI ARABIA.

The tower is guyed at 5 heights and in 4 equidistant points in the ground. It takes only less than fifteen minutes to erect the tower during a non-windy day. Our experience reveals that the most suitable time to erect the tower is just after sunrise. A maximum of four technical staff can easily install the wind assessment station. The map of Saudi Arabia illustrated in Figure 1 shows the locations of the wind monitoring stations.

DATA ANALYSIS

The wind assessment stations are located 500 km (Dhahran, the nearest) and 1200 km (Arar, the farthest) away from Riyadh. To maximize data collection and minimize site visits, the DAS were programmed to store data (averaging interval) every 30 minutes. This requires only one site visit every 3 months for data retrieval and for station's hardware maintenance. The Riyadh station is only 2 km away

from the office, thus, its averaging interval was programmed to ten minutes while its data retrieval is performed every two weeks. Retrieving the data is procedural in nature. First the PCMCIA card is taken out from the DAS. It is then inserted to a card reader which is serially configured to a PC compatible notebook computer. A computer program is run to retrieve the raw data from the card and to convert the raw data into an ASCII, comma delimited structure. The converted file is imported to EXCEL applications program for data processing and analysis to generate periodic statistics, tables and graphs.

Mean Wind Speed

The wind speed data for the selected three sites for a period of two years are analysed. The mean wind speed is calculated by the hour, daily and monthly using the arithmetic average of 10 minute values for the Riyadh station and the 30 minute values from the Arar and Dhahran stations. The standard deviation of the hourly average is calculated from the ten minute data while the daily standard deviation is calculated from the hourly average data. The monthly mean wind speed of the three stations, at height of 40 m, is shown in Figure 2.

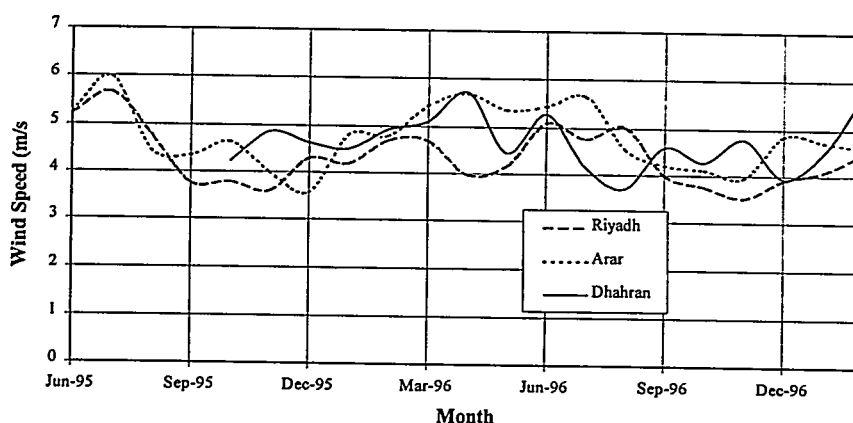


FIGURE 2. THE MONTHLY AVERAGE WIND SPEED FOR THE THREE STATIONS.

Table 2 shows the mean wind speed of each site and its corresponding standard deviation (SD). WS20, WS30 & WS40 correspond to the mean wind speed at heights 20, 30 and 40 m respectively. As reported previously, the mean wind speed of the sites in all heights are almost identical (Alawaji, et al., 1996). The mean wind speed in Ar-ar is the highest among the stations at all heights. Its maximum mean wind speed occurs Mar - Jul while the minimum mean wind speed occur during the period Oct - Dec. Riyadh has the lowest wind speed among the three regions. The maximum mean wind speed occur during the period May - Jul while the minimum mean wind speed occur during Nov and Dec. In Dhahran, maximum mean wind speed is during Jan - March while the minimum mean wind speed is during Jul - Dec.

Saudi Arabia's season can be categorised to hot and cold climate. Hot season usually starts from April to September, while the cold season is from October to March. In Riyadh and Dhahran during hot season, the maximum ambient temperature during a typical day reaches 42 °C. During cold season, the average temperature is about 16 °C. Since Arar is situated in the northern part of the country, its average ambient temperature is lower compared to the two sites.

TABLE 2. AVERAGE WIND SPEED, STANDARD DEVIATION AND PREVAILING WIND DIRECTION.

Wind Station	WS20 (m/s)	SD20	WS30 (m/s)	SD30	WS40 (m/s)	SD40	Prevailing Wind Direction
Ar-ar	4.40	1.58	4.77	1.67	5.18	1.78	SSE
Dhahran	4.33	1.48	4.66	1.58	4.85	1.70	N
Riyadh	3.79	1.25	4.09	1.34	4.37	1.41	N/SE

The seasonal variation of average wind speed for two sites, 40 m height are shown in Figures 3.1 and 3.2. M1, M2...M6 in the X axis represent the months during hot season (April - September) and during cold season (October - March).

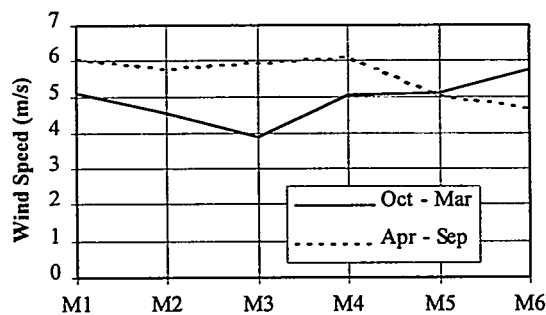


FIGURE 3.1 ARAR SEASONAL VARIATION

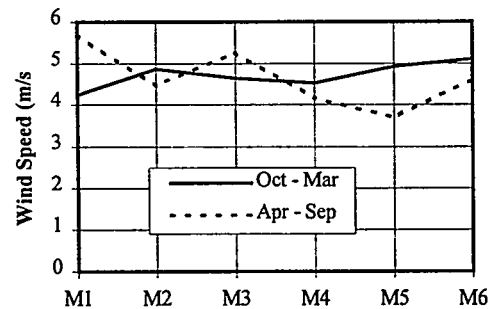


FIGURE 3.2 DHAHRAN SEASONAL VARIATION

In Arar, the average wind speed is higher during hot season. As the ambient temperature drops, the average wind speed also decreases considerably. The same is true in Riyadh. However, in the coastal area of Dhahran, the average wind speed is more during cold season.

Wind Speed Frequency Distribution

Wind speed frequency distribution was determined at a bin interval of 1 m/s. Table 3 shows the distribution of wind speed in the three regions. The Riyadh area has wind speed below 4 m/s, 40% of the time. Considering a wind machine with a cut-in speed of 4 m/s, power availability only occur just above 50% of the time. At 40 meter height, wind is nearly distributed equally into 3 bins, 30% is below 4m/s and 35% each of the bins 4-5 m/s and above 5 m/s. In Dhahran and at height 20 m, the usable mean wind speed occurs only 60% of the time. However, the occurrence of mean wind speed between 3 and 8 m/s at all heights is 70%. The same distribution is observed in Arar, though is slightly higher. At heights 40 m, the higher mean wind speed are nearly having the same distribution.

Diurnal and Seasonal Variation of Mean Wind Speed

The diurnal variation of mean wind speed, at 40 m height, is shown in Figure 5. It describes the wind characteristic in the three places during a typical day.

TABLE 3. WIND SPEED FREQUENCY DISTRIBUTION AT DIFFERENT HEIGHTS IN METERS.

Speed (M/S)	Arar			Dhahran			Riyadh		
	20	30	40	20	30	40	20	30	40
0	0.66	0.77	0.59	0.56	0.47	0.49	1.13	1.17	1.02
Below 4	29.73	24.26	23.28	29.90	25.41	24.21	39.14	33.54	29.28
4 - 5	34.77	29.50	26.50	37.24	35.04	24.06	36.31	36.32	34.97
6 - 7	23.31	26.44	26.53	20.44	24.06	25.93	17.17	20.57	23.54
Above 7	12.19	17.41	24.55	12.42	15.48	18.04	7.38	9.57	9.17

In Riyadh and Dhahran, wind speed is higher during day time. Its increase begins at sunrise. In Dhahran, wind blows stronger during the time 14:00 - 18:00 hrs, while in Riyadh, wind speed is more from 16:00 hrs until after 20:00 hrs. The wind speed in Riyadh area stabilises after it reaches its peak at 10:00 hrs. The Arar area has a very smooth wind patten. It is more during night time while its minimum mean wind speed occur mid day.

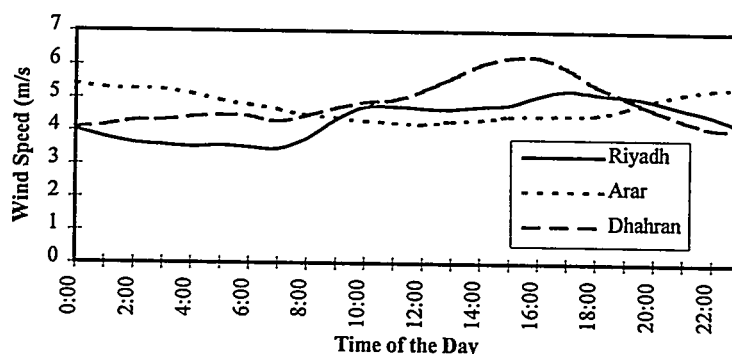


FIGURE 5. DIURNAL VARIATION OF MEAN WIND SPEED.

The wind characteristic also varies by season. Table 4 lists the mean wind speed of the three sites at different heights for the complete year, 1996. In Dhahran, the average mean wind speed during day time is 32% greater than during night time. This difference occurs during the period April - June. For the complete year, the mean day wind speed is nearly 20% more than the mean night time wind speed. In Riyadh, the difference for the whole period is only 4%. In Arar, average night time wind speed is 8.2% greater than that during day time. During the period April - June the mean night time wind speed is 13.3% higher than day time.

Wind Direction Frequency Distribution

Analysis of wind direction is conventionally represented by a wind rose. The frequency distribution of the wind direction for all the station were distributed equally into 16 bins at 22.5° per bin. Table 2 lists the prevailing wind direction for each stations. The term prevailing wind means that the wind blows from one direction more commonly than the others. This direction is caused by the topographic characteristic of the site (WMO, 1981). The prevailing wind direction in Riyadh has been found to change seasonally. During

cold season, the wind direction is south-east, during hot season, wind comes from the north. Dhahran's prevailing wind direction is from the north while in Arar, wind comes from south - south-east.

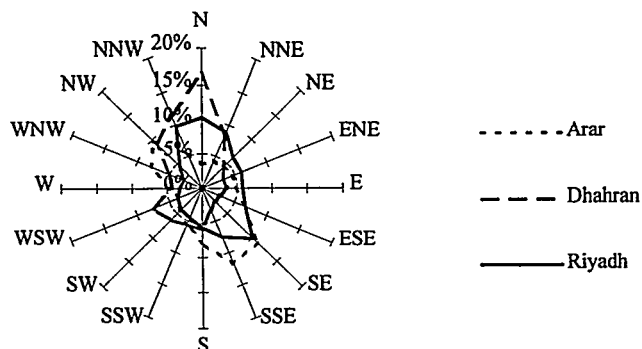


FIGURE 6 . FREQUENCY DISTRIBUTION OF WIND DIRECTION.

TABLE 4. SEASONAL VARIATION OF WIND SPEED FOR THE YEAR AT HEIGHT 40M, 1996.

TIME	January - March			April - June			July - September			October - December		
	AR	DH	RY	AR	DH	RY	AR	DH	RY	AR	DH	RY
00:00	4.93	4.41	4.38	6.45	4.12	4.20	5.29	3.21	4.46	4.69	4.10	3.60
01:00	4.8	4.39	4.22	6.22	4.21	3.88	5.43	3.21	4.41	4.32	4.16	3.39
02:00	4.78	4.61	4.18	6.08	4.27	6.61	5.37	3.40	4.26	4.39	4.16	3.29
03:00	4.96	4.54	3.93	6.07	4.26	3.65	5.66	3.35	4.34	4.36	4.11	3.21
04:00	4.91	4.55	3.76	6.01	4.37	3.50	5.57	3.45	4.44	4.22	4.20	3.01
05:00	4.81	4.63	3.86	5.71	4.46	3.59	5.40	3.46	4.36	4.23	4.28	3.11
06:00	4.8	4.55	3.82	5.47	4.36	3.41	5.25	3.48	4.34	4.29	4.25	3.16
07:00	4.81	4.34	3.87	5.15	4.42	3.37	5.16	3.60	4.34	4.19	3.94	2.99
08:00	4.53	4.66	3.90	5.48	4.96	4.07	5.27	3.62	4.48	3.88	3.88	3.04
09:00	4.8	4.91	4.49	5.57	5.53	4.76	4.91	4.05	4.57	3.71	4.04	3.79
10:00	5.17	5.11	5.04	5.29	5.65	4.69	4.50	4.30	4.89	3.84	4.22	4.34
11:00	5.25	5.05	5.07	5.12	5.79	4.67	4.23	4.46	5.17	3.95	4.34	4.26
12:00	5.13	5.40	5.03	4.92	6.24	4.57	4.30	4.61	5.24	3.95	4.69	4.06
13:00	5.14	5.72	4.92	4.71	6.97	4.53	4.50	5.05	5.40	4.18	4.95	3.87
14:00	5.15	5.86	4.98	4.78	7.46	4.71	4.45	5.61	5.46	4.19	5.27	3.66
15:00	5.17	5.89	4.90	4.73	7.55	4.63	4.63	5.84	5.52	4.24	5.65	3.68
16:00	5.16	6.02	5.10	4.89	7.51	5.12	4.70	5.92	5.46	4.26	5.67	3.87
17:00	5.04	5.65	5.09	5.02	6.97	5.43	4.65	5.90	5.57	4.18	5.41	4.09
18:00	4.87	5.44	5.00	4.95	6.13	5.17	4.51	5.39	5.41	4.45	5.03	4.31
19:00	5.03	5.29	4.86	4.98	5.56	5.56	4.55	4.80	5.33	4.83	4.89	4.49
20:00	5.38	5.16	4.76	5.33	5.11	5.43	4.87	4.14	5.17	4.78	4.57	4.37
21:00	5.38	4.97	4.74	5.87	4.59	4.77	3.55	3.55	4.81	4.73	4.36	4.15
22:00	5.23	4.68	4.86	6.25	4.33	4.56	3.30	3.30	4.80	4.65	4.18	3.92
23:00	4.99	4.59	4.42	6.58	4.21	4.38	3.28	3.28	4.58	4.66	4.12	3.69

Mean Power Density

Wind power is defined as the flux of kinetic energy passing through the cross sectional area of the blade of wind energy conversion system(WECS). Theoretically, wind available power, P_a is given by the relation

$$P_a = \frac{1}{2} \rho A V^3 \quad (\text{Eq. 1})$$

where ρ is the air density in kg/m^3 , A is the cross section area (m^2) and V is the wind speed (m/s). Equation 1 shows that the wind power is a cubic function of the wind speed. However, the maximum extractable power P_e from a Wind Energy Conversion System (WECS) is only 59.3% of P_a (Wegley, et al., 1980).

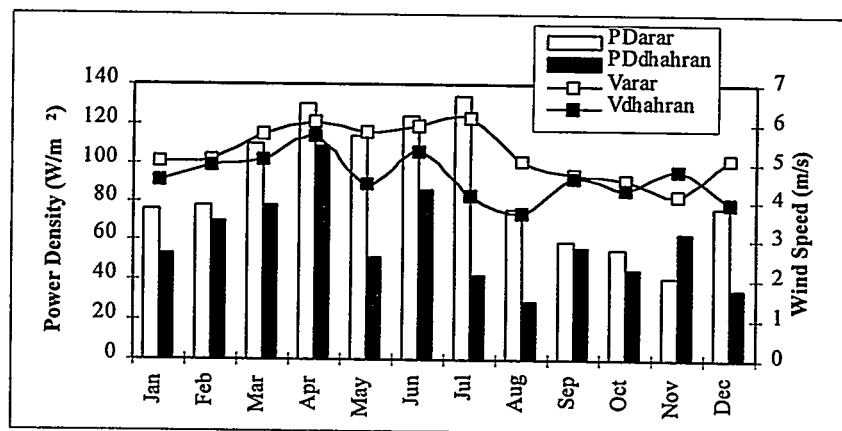


FIGURE 7. POWER DENSITY AND MEAN WIND SPEED AVAILABLE IN ARAR AND DHAHRAN.

Figure 7 presents the power density available in two sites, Dhahran and Arar, during 1996, in W/m^2 . Shown also is the monthly mean wind speed at 40 m height of each site. The power density when multiplied by the diameter of the blade of a wind machine will result to the generated power for that given time. The annual power density for the year 1996 in Arar and Dhahran is 172 and 115 W/m^2 respectively.

LESSONS LEARNED

Several lessons were learned in operating remote wind assessment stations. These can be summarized as follows:

1. The most appropriate averaging interval for data collection is 30 minutes. This interval provides maximum raw data collection and minimize site visit for data retrieval to 4 times a year, thus, decreasing operational costs. This interval is the optimum for the life of the DAS

hardware. Lowering the interval increase power utilization, thus, decreasing the life of the battery.

2. Corrosion has affected the wind station hardware in the coastal areas due to very high relative humidity. Measures should be taken to protect the hardware from rust. Material and equipment for the tower should be corrosion resistant to avoid fast hardware wear and tear. Tower sections should also be painted. The hardware fixing the tower to the ground (guy wire, U-bolts and nuts and anchors) should be made of stainless steel.
3. The stations undergo maintenance every year with the towers brought down. This interval is recommended because of the following experiences:
 - i. Dust and fine sand (in the desert environment) and sticky sand in the coastal areas, due to high humidity, stick to the surfaces of the station hardware. The dirt had damaged several sensors. Fine sticky sands were also found in the surfaces of the anemometer cups as well as the wind vanes. The accumulation of dirt could degrade data measurements.
 - ii. Replacement of failed wind speed and wind direction sensors.
 - ii. Cleaning the wind sensors increases operations efficiency and data reliability. Other meteorological sensors (insolation, ambient temperature and relative humidity) were also found dirty. The sensors were dipped into a pail of water to remove the accumulated sand.
 - iii. Corroded parts of the tower such as U-bolts, U-clamps, nuts and cable clamps need replacements. To be replaced also is the busted bulb of the obstruction light.
 - iv. Clamps of the power and signal cables fixed into the tower were found loose.

CONCLUDING REMARKS

The north and coastal areas of Saudi Arabia presents an average wind speed that could be used for power extraction. In Arar, mean wind speed is nearly equal the whole day though, slightly higher during night time. The annual mean wind speed at 40 m height is above 5 m/s which generate a considerable amount of power. The Dhahran area has a lower annual mean wind speed. However, its hourly diurnal variation of mean speed shows that there is a tremendous increase of wind speed between 12:00 hrs and 19:00 hrs. The wind speed increases by 38% to as much as 50%. It should also be noted that the change in wind speed coincide with the change of the power utility load. . The central region has lowest mean wind speeds among the three regions at 4.37 m/s.. The annual extractable energy density in Arar, Dhahran and Riyadh at a height of 40 m are found to be 890, 599 and 488 kWh/m². Cut-in wind speed of medium size wind turbines nowadays are lowered without affecting their overall efficiency. This development and added to the distinct characteristic of wind in the areas and their energy density availability presents a prospect of wind energy conversion and utilization. However, further study has to be done to find the appropriate application of wind energy for practical utilization in the these areas. It is still the goal of the wind program to continue assessing wind potential of other localities in the country.

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WIND DATA ANALYSIS FOR THE DESIGN OF A HYBRID GENERATION SYSTEM AT THE ALGODOAL ISLAND - BRAZIL

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ABSTRACT

The northeastern coast of the State of Pará and the Marajó Island - in Brazil, exhibit a wind potential that seems adequate to the generation of electric energy to supply local demands. These local demands are mostly formed by small towns and villages located invariably far from the big urban centers with little or no possibility to be supplied by the utility grid. In this paper it is intended to report the studies being conducted to design a hybrid wind diesel system to attend a small population center, namely the Algodoal Island, that is a representative sample of this region. It will be described the process of data acquisition and statistical treatment as well as some environmental, social and economic aspects regarding the Algodoal Island. Finally it will be presented a preliminary estimate of energy demand for this locality as well as a probable wind-diesel system arrangement to supply this demand.

INTRODUCTION

The energy generation model widely used in the island regions and small localities in the inland part of the Amazon Region is based on diesel-electric generation, which although presenting an initial low cost investment, may exhibit a lot of long-term maintenance problems, aggravated by transportation difficulties of this fuel to localities far away from fueling centers.

Also, due to economic impossibility these communities will never be supplied by the grid since it is very expensive to construct long transmission lines and substations to feed these small load demands.

Within this view, using renewable energy together with conventional resources is quite possible as there is a considerable reduction of maintenance costs of such systems, reinforcing its sustenance. This is the case of the Algodoal Island, whose planned energy supply system will be formed by wind power and diesel generation, in this case, being the diesel units mainly to reinforce the system global reliability.

In this manner, studies aiming at the definition of a hybrid system to supply the urban center of Algodoal Island are being conducted. In this way, local demand studies and solar and wind power potentiality surveys are being carried out, to serve as a base for the hybrid project elaboration, which will meet the energy needs of the island population center.

THE ISLAND OF ALGODOAL

Algodoal is a windy spot located in the northeastern coast of the State of Pará - Brazil, facing the Atlantic Ocean., with latitude $0^{\circ} 35' S$ and longitude $47^{\circ} 35' W$. Its climate is characterized as tropical and the temperature oscillates around 25 and 35 degrees centigrade during the whole year. It is located approximately 200 Km far from Belém, the Capital of the State of Pará, and is reached by car and boat. Its principal economic activities are based on fishing and tourism, with small local population estimated as 1,000 inhabitants almost all year long, except during the months of January, February and July, when many people go to spend their vacations at the island and this population may reach approximately 2,000 inhabitants. In addition, its present energy supply is based on many small private diesel units and there is no short-term perspective of grid supply from the local electric utility.

WIND DATA MEASUREMENTS ^[1]

To assess the wind energy potential, a 30 meter high computerized meteorological station was installed on a self-sustained tower, located approximately 1 km far from the load center.

The wind speed is measured by a 3-cup anemometer with operating range from 0 to 50 m/s and gust survival to 60 m/s. Its threshold sensitivity is 0.5 m/s, using a tach-generator to transform speed to dc voltage (1800 rpm = 2400 mV = 28.6 m/s).

The wind direction is measured by a vane with operating range of AZ 360° mech or 355° elec (5° open), gust survival to 60 m/s, threshold sensitivity of 0.7 m/s at 5° displacement.

The meteorological station was installed on January 15th, 1996, and the data have been collected at every 60 days. The data are acquired continuously and magnetically registered with time spans of 10 minutes.

After acquisition, the raw data have been treated statistically at Universidade Federal do Pará, by the Group of Study and Application of Solar and Wind Energies (GEAESE), using basically the Excel Package from Microsoft. The results here presented correspond to a one year analysis, although we have already gotten available data for a period of 1 year and 4 months.

WIND DATA STATISTICS

Figure 1 presents the raw data of wind speed for a period of one day, exactly as they were registered by the anemometer. This day was selected as a typical day of the season period starting in July and ending in December, when the highest wind speeds occurred. It can also be seen that the wind speed is fairly regular not presenting occasional gusts. The absence of gusts is a basic characteristic of the wind profile at the Algodoal Island.

A very interesting feature can be noted by observing Figure 2, in which the monthly mean values of wind speeds from January to December of 1996, are depicted. Two distinct patterns of wind regime can be recognized. The period from January to June is dominated by a low wind speed regime, which is coincident with the rainy season in this region. From July to December that corresponds to the dry season and it rains only occasionally, the wind regime is higher which confirms a natural characteristic of this region of exhibiting weak winds during the fall and strong winds during the spring.

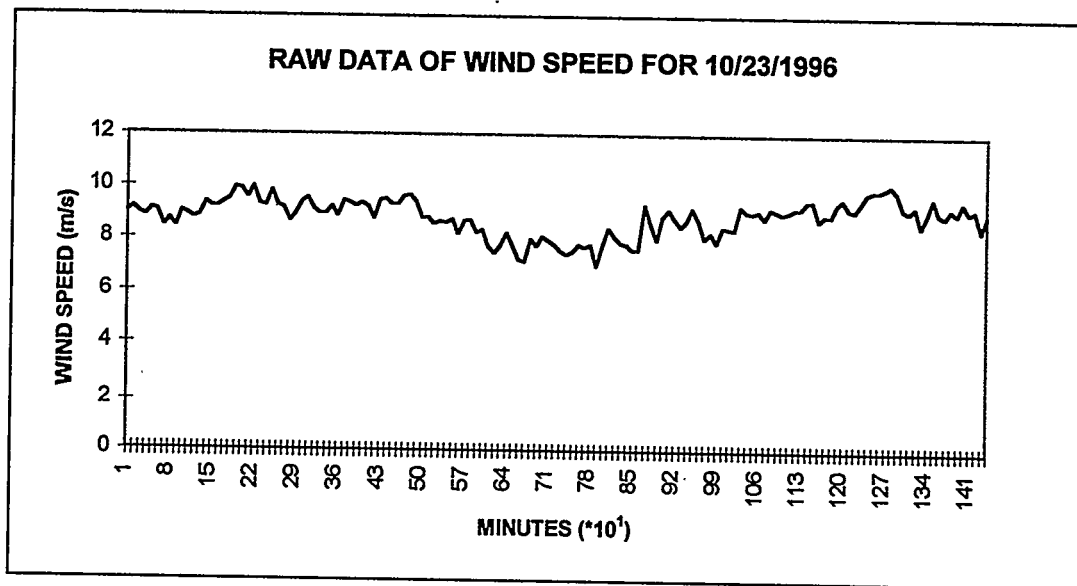


FIGURE 1- RAW DATA OF WIND SPEED FOR 10/23/1996

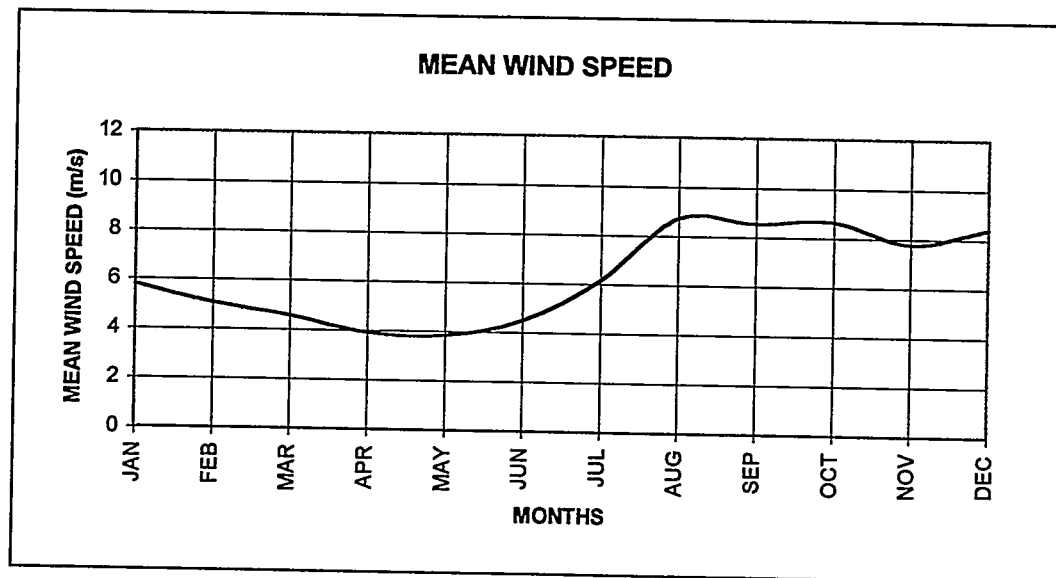


FIGURE 2- MONTHLY MEAN VALUES OF WIND SPEED FROM JANUARY TO DECEMBER OF 1996

The per cent distribution of wind speed presented in Figure 3 remarks the characteristic of low wind speed that dominates this region. It can be seen that wind speeds higher than 10 m/s rarely occurred. This is an important feature that may decide the most convenient wind turbine technology to be used in this region.

PERCENTUAL DISTRIBUTION OF WIND SPEED FROM JANUARY TO DECEMBER OF 1996

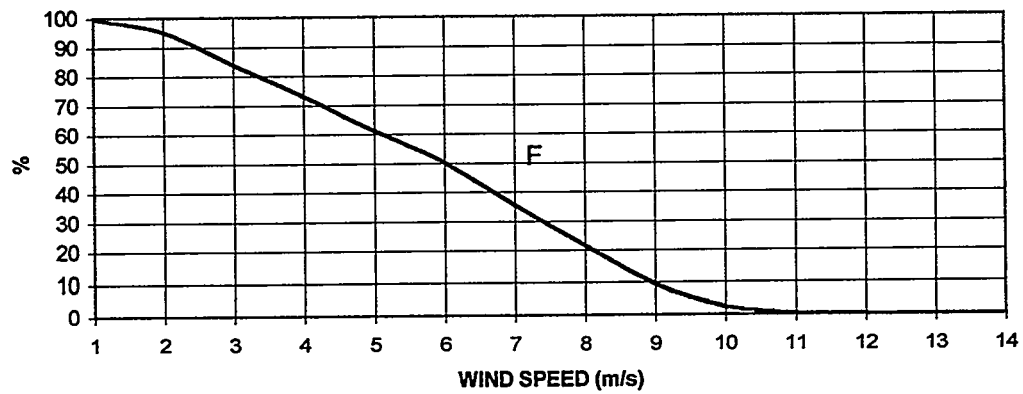


FIGURE 3- PERCENT DISTRIBUTION OF WIND SPEED
FROM JANUARY TO DECEMBER OF 1996.

Figure 4 presents the Weibull distribution for the monthly mean values displayed in Figure 2. For these data it was adjusted a Weibull distribution with a scale factor $c=7.351$ m/s and a shape factor $k=2.835$, which reinforces the fact that low wind speeds are regular and prominent in this region.

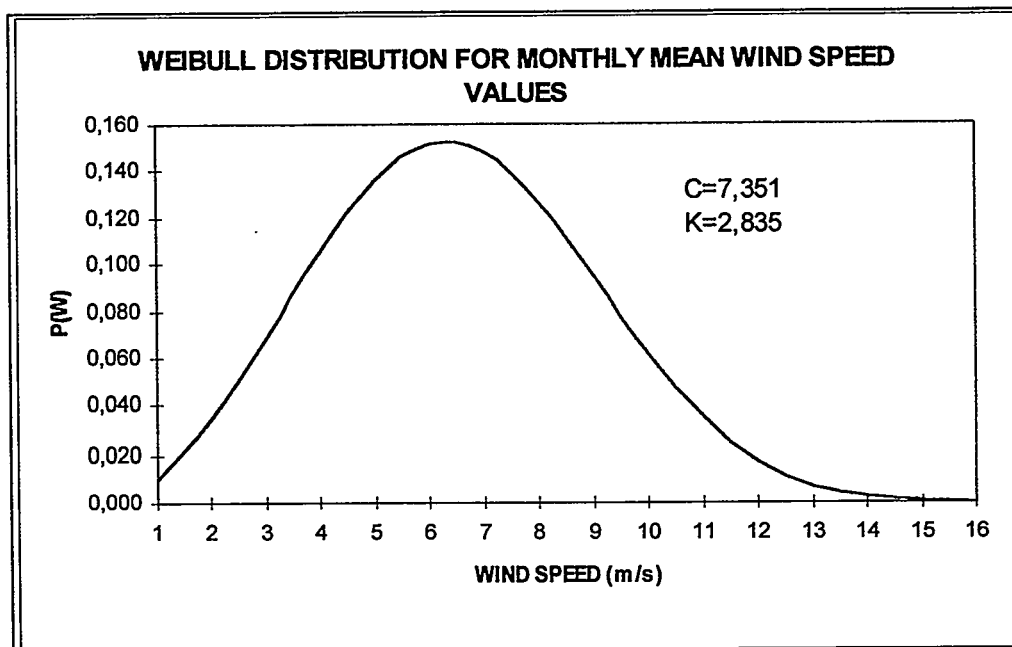


FIGURE 4- WEIBULL DISTRIBUTION FOR MONTHLY MEAN WIND SPEED VALUES

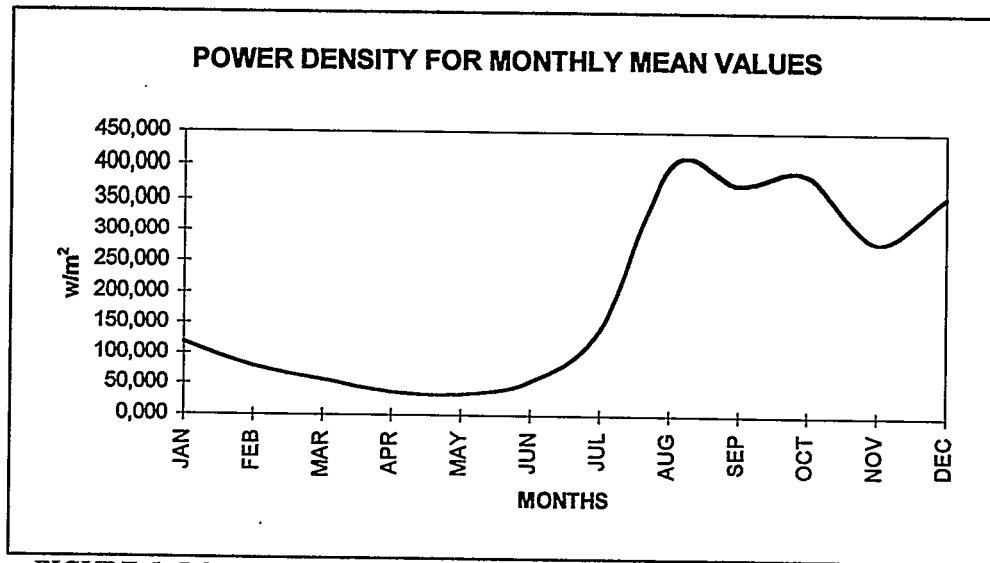


FIGURE 5- POWER DENSITY FOR MONTHLY MEAN VALUES

The power density available in the air mass for the monthly mean wind speed values presented in Figure 2 was obtained ^[2] using equation (1) and the results are depicted in Figure 5.

$$P/A = \frac{1}{2} \rho v^3 \quad (1)$$

where:

P/A - power density in (watts/m²)
 v - wind speed in (m/s)
 ρ - air density (≈ 1,2 kg/m³)

Again from January to June it is shown a low power density while for the rest of the year this relation is fairly higher.

Finally, a mean annual day is presented in Figure 6. The wind speed values depicted in this curve are hourly mean values taking into account all the days of the year.

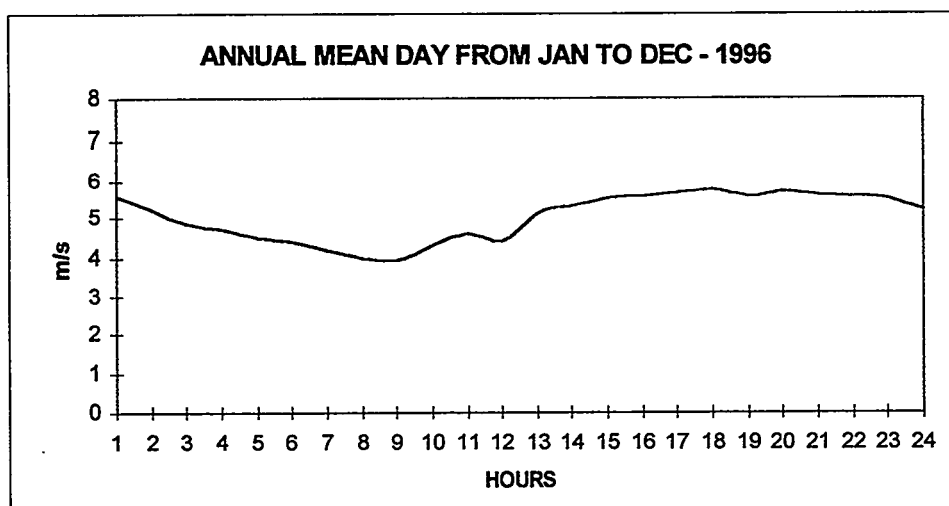


FIGURE 6- PROFILE OF MEAN SPEEDS FOR A MEAN ANNUAL DAY

LOCAL DEMAND ESTIMATE

By in-loco survey ^[3] it was identified that the urban center of the Algodoal Island is composed of 325 buildings, grouped as 299 residential buildings, 21 commercial establishments, and 5 public buildings represented by 2 schools, 1 medical office, 1 telephone office and a local market still under construction. The commercial establishments are made up of 6 small hotels, 5 restaurants and snack bars, 3 grocery stores and 1 bakery. The residential buildings were classified according to their built areas as: 108 big houses (80 m² - 130 m²); 101 medium houses (50 m² - 80 m²); and 90 small houses (40 m² - 50 m²). Assuming a monthly energy consumption of 60 kWh per residence, 104 kWh per commercial and public buildings and also considering losses and other consumers like public lightning and unforeseen demands, table 1 presents the expected yearly energy consumption and the corresponding maximum load demand using a demand factor (DF%) around 26%, which is a usual value for these applications. Also, a growing factor was considered to obtain the expected energy consumption for the coming years until 2008.

TABLE 1- LOCAL DEMAND ESTIMATES FOR THE ALGODOAL ISLAND

Year	Consumer Type				Losses MWh	Energy MWh	DF %	Max Load(kW)
	Resid MWh	Commer MWh	Others MWh	Total MWh				
1997	215	26	57	298	33	331	26.0	145
1998	243	30	66	339	38	377	26.0	165
1999	261	35	72	368	42	410	26.1	179
2000	269	36	75	380	42	422	26.1	184
2001	276	40	77	393	44	437	26.2	190
2002	283	41	79	403	44	447	26.3	194
2003	289	46	81	416	45	461	26.4	200
2004	304	46	83	433	46	479	26.4	207
2005	310	51	86	447	47	494	26.5	213
2006	318	52	87	457	47	504	26.6	216
2007	324	57	89	470	48	518	26.7	221
2008	330	58	91	479	48	527	26.7	226

FINAL REMARKS

In view of the wind data characteristics and the local load demand estimates for the Algodoal Island formerly presented, some general guidelines can be stated concerning the specification of the wind-diesel generation system to this site:

1. The results presented in Figures 2 and 5 demonstrate clearly that the diesel generation may play an important role as a complementary generation source, during the period from January to June when the lowest wind speeds and power densities are verified.
2. A hint to select the most adequate WEC for this site can be extracted from the results depicted in Figures 3 and 4. According to these results an appropriate choice will rely on a wind turbine assembly that operates more efficiently in the range of low speeds, namely from 5 m/s to 8 m/s.
3. The cut-in speed should be as low as possible to take advantage of the low speed characteristic of the wind profile.
4. The cut-out and gust survival velocities are not critical. The highest value of wind speed registered during the year was about 18 m/s that rarely occurred during the months of August, September and October.
5. Preliminary studies suggest that a wind farm arrangement composed of small wind turbine units in the range of 50 kW each, summing up to 300 kW by the year of 2008 may be sufficient to supply the expected load demand as presented in Table 1.

ACKNOWLEDGMENTS

The authors are grateful to Universidade Federal do Pará (Federal University of Pará), CELPA - Centrais Elétricas do Estado do Pará S.A. (The Local Utility), and CEPEL - Centro de Pesquisas em Energia Elétrica (Research Center of Eletrobras) for supporting these preliminary studies. Further results concerning the detailed project elaboration will be presented in future publications.

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RESULTS FROM UTILITY WIND RESOURCE ASSESSMENT PROGRAMS IN NEBRASKA, COLORADO, AND ARIZONA

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ABSTRACT

Global Energy Concepts (GEC) has been retained by utilities in Colorado, Nebraska, and Arizona to site, install, and operate 21 wind monitoring stations as part of the Utility Wind Resource Assessment Program (U*WRAP). Preliminary results indicate wind speed averages at 40 meters (132 ft) of 6.5 – 7.4 m/s (14.5-16.5 mph) in Nebraska and 7.6 – 8.9 m/s (17.0-19.9 mph) in Colorado. The Arizona stations are not yet operational. This paper presents the history and current status of the 21 monitoring stations as well as preliminary data results. Information on wind speeds, wind direction, turbulence intensity, wind shear, frequency distribution, and data recovery rates are provided.

BACKGROUND

U*WRAP is intended to provide technical and financial assistance to utilities conducting wind resource assessments for potential wind energy development. Guidelines were developed for U*WRAP to provide consistency in data collection, analysis, and reporting. U*WRAP is funded by the Department of Energy and administrated by the Utility Wind Interest Group (UWIG).

GEC is currently conducting the U*WRAP activities for a consortium of utilities and other interested groups in Nebraska under the Nebraska Power Association (NPA); a consortium of utilities in Colorado led by the Public Service Company of Colorado (PSCo.); and Tucson Electric Power (TEP) in Tucson, Arizona. GEC is responsible for siting the monitoring locations, installing the monitoring equipment, and maintaining and operating the monitoring stations for these three programs. GEC also processes the data and submits the necessary documentation to meet all U*WRAP requirements.

MONITORING SITE OVERVIEW

GEC conducted site surveys to locate potential areas for wind monitoring activities in each state. These sites were then ranked according to the following criteria:

- wind resource
- land availability
- terrain suitability
- utility access
- physical access
- logistical support
- public and environmental sensitivity
- landowner acceptance
- communication access

Final site selection was completed based on the overall site ranking, input from the utilities involved in the program, and ease in obtaining permits and leases.

NEBRASKA

Eight monitoring stations were installed throughout the state of Nebraska in April 1995. All data is available in the public domain. A description of each monitoring site follows:

Site 101 – Imperial: This station is located in Chase County within a few miles of the Colorado border in southwestern Nebraska. The station is well exposed in complex, hilly terrain in the sand hills at an elevation of 1,035 meters (3,400 ft.).

Site 102 – Rushville: This station is located in northwest Nebraska in Sheridan County on an east-west ridgeline two miles northwest of the town of Hay Springs. The surrounding area consists of diverse terrain and ground cover including areas that are forested and complex. The elevation is 1,190 meters (3,900 ft.).

Site 103 – Winnebago: This station is located in northeast Nebraska in Thurston County on a well exposed ridgeline midway between the towns of Winnebago and Macy, three miles west of the Missouri River. The site is in elevated, hilly terrain that separates the river valley from Nebraska's eastern plains at an elevation of 460 meters (1,500 ft.).

Site 104 – Wahoo: This station is located in eastern Nebraska approximately 30 miles north of Lincoln. The site is in the rolling hills of west central Saunders County in a well-exposed location at an elevation of 520 meters (1,700 ft.).

Site 105 – Kimball: This station is located in Kimball County south of Kimball in the southern part of the Nebraska panhandle. The site is on flat to gently rolling terrain which gains elevation toward the western state border with Wyoming. The elevation is 1,465 meters (4,800 ft.).

Site 106 – Valentine: This station is located in northern Nebraska in Cherry County in the high plains north of Valentine within five miles of the Nebraska-South Dakota border. The plains run for miles along the state border and are significantly higher in elevation than areas to the south where the town of Valentine is located. The elevation is 885 meters (2,900 ft.).

Site 107 – Springview: This station is located in northern Nebraska in Keya Paha County on a gentle east-west ridge approximately one mile west of the town of Springview. Similar terrain runs for miles east and west of Springview and is bordered by lower terrain to the north and south. The elevation is 765 meters (2,500 ft.).

Site 108 – Stuart: This monitoring station is located in northern Nebraska in Holt County approximately six miles north of the town of Stuart. The site is in a well-exposed location in the broad plains that are characteristically divided by tree shelterbelts along property boundaries. The elevation is 825 meters (2,800 ft.).

COLORADO

Ten monitoring stations were installed in Colorado from April 1996 to October 1996. Details on each monitoring station are provided below. Site data and exact locations are not public information at this time.

Site 201: This station is located in northeastern Colorado in the sand hills at an elevation of 1,215 meters (3,985 ft.).

Site 202: This station is located on a mesa in southeastern Colorado near the Colorado-New Mexico border. The elevation is 2,020 meters (6,630 ft.).

Site 203: This station is located in southeastern Colorado on very flat terrain on a modest ridge. The elevation is 1,375 meters (4,510 ft.).

Site 204: This station is located approximately 10 miles from Site 203 in southeastern Colorado on very flat terrain. The elevation is 1,315 meters (4,310 ft.).

Site 205: This station is located in eastern Colorado on a well-exposed ridge with an east-west orientation. The elevation is 1,410 meters (4,320 ft.).

Site 206: This station is located in east central Colorado on predominantly flat terrain with gently rolling terrain to the East. The elevation is 1,675 meters (5,500 ft.).

Site 207: This station is located in central Colorado in a well-exposed location on flat to gently rolling terrain at an elevation of 2,115 meters (6,935 ft.).

Site 208: This station is located in northeastern Colorado in a very well exposed location with a south facing escarpment at an elevation of 1,395 meters (4,570 ft.).

Site 209: This station is located in northeastern Colorado, west of Site 208, on gently rolling terrain. The elevation is 1,600 meters (5,250 ft.).

Site 210: This station is located in north-central Colorado on rolling terrain at an elevation of 2,145 meters (7,040 ft.).

ARIZONA

GEC will install 3 monitoring stations for TEP in eastern and southeastern Arizona. Site surveys were completed in April 1996. Complications with permitting for these sites have delayed the installation of the monitoring equipment. TEP expects to complete the permitting process within a few months. The site data and locations are not public information at this time. Site descriptions are as follows:

Site 301 – Springerville North: The hills north of the town of Springerville exhibit ridge effects and funneling. The elevation in the hills varies from 2,285 to 2,375 meters (7,500-7,800 ft.).

Site 302 – Springerville West: The rolling range land west of the town of Springerville is very well exposed to the prevailing southwest winds. The elevation varies from 2,285 to 2,375 meters (7500-7800 ft.).

Site 303 – Rain Valley: The Rain Valley is located about 10 miles east of Sonoita. The terrain is flat to gently rolling with mountains southwest of the site. The elevation of this area ranges from 1,435-1,495 meters (4,700-4,900 ft.) in the flat lands to 1,585-1,830 meters (5,200-6,000 ft.) in the ridge tops.

EQUIPMENT CONFIGURATIONS

The wind monitoring equipment for all U*WRAP stations is provided by NRG Systems. All basic parameters required for U*WRAP are recorded at each station as well as some optional parameters. A diagram of the tower configuration is provided in Figure 1. The following is a description of the monitoring equipment installed in Colorado and Nebraska (the Arizona program will utilize the same equipment):

correlation to another functioning sensor on the same tower, a sensor on a neighboring tower, or data from a nearby weather station. If a good correlation cannot be established the data is replaced with the diurnal average for good data in the same month.

The average data recovery rate for the Nebraska and Colorado programs is 95%. This represents the percentage of wind speed data remaining after erroneous data have been removed in the quality check process. Although the majority of the lost data is due to sensor icing, lightning is of the greatest concern as this can cause permanent damage to the monitoring equipment. NRG grounding kits (4 ft. lightning spikes and 8 ft. ground rods) were installed at all stations.

Due to the frequent damage experienced at the Nebraska stations during the initial year of operation, additional lightning mitigation measures were installed at four stations to test the effectiveness of various equipment. These measures were installed at Sites 102, 103, 106, and 107 in October 1996. There have been no lightning related failures at these four stations since the additional measures were installed.

The Colorado station also experienced a significant number of anemometer failures at the 40 meter level during the first few months of the program. All 40 meter anemometers were replaced with grounded anemometers in October 1996. There have been no lightning related failures since this time.

RESULTS

Figure 2 provides the average wind speeds at 40 meters and predominant wind direction for regions of Colorado and Nebraska. The period of record for all eight Nebraska stations is 2 complete years and for the Colorado stations it varies from 5 months to 1 year. Only the wind speed ranges are available for Colorado as site specific information is not public at this time. The Nebraska data can be obtained through the internet at <http://hppcsun.unl.edu/wind>.

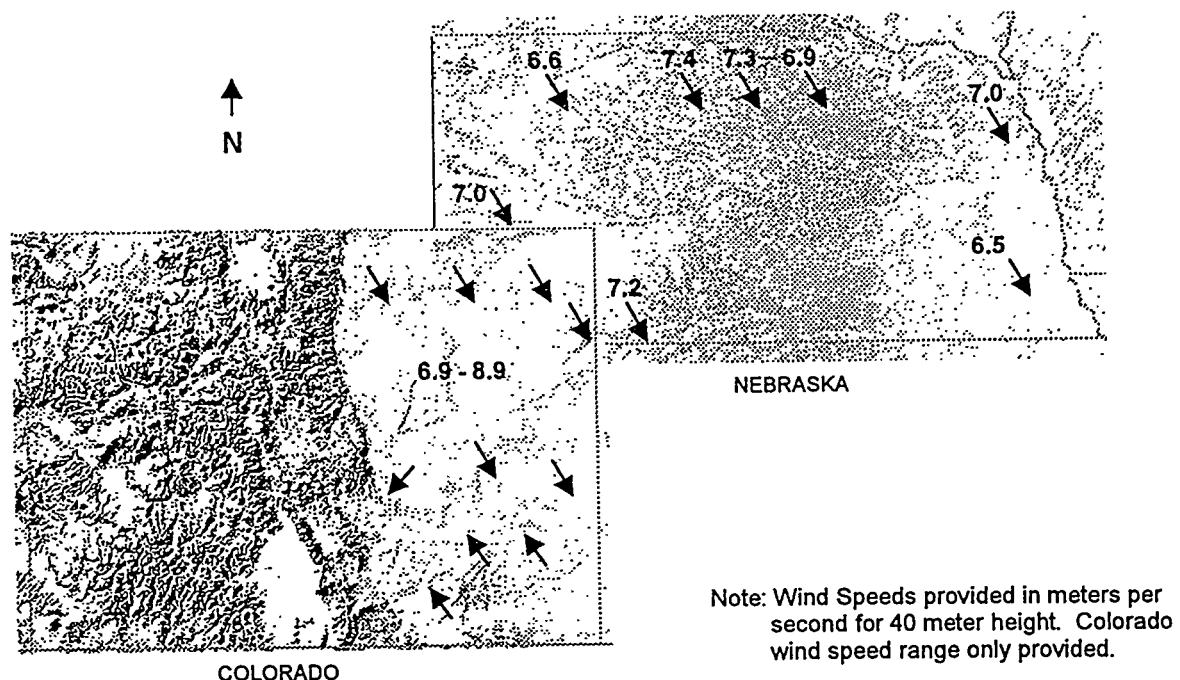


FIGURE 2. REGIONAL WIND SPEEDS AND DIRECTIONS IN COLORADO AND NEBRASKA

- 40 meter (132 ft.) NRG TallTower, 150 mm (6.0 in.) diameter, with guy wires
- NRG 9300 CELLogger or TelePort Logger with 12 Volt battery, two 9 Volt backup batteries, solar panel for battery recharging, and 256 kbyte Data Card
- NRG #40C Maximum Calibrated Anemometers at 10, 25, and 40 meters with a redundant sensor at 40 meters
- NRG #200P Wind Direction Vanes at 25m and 40m
- NRG #110S Temperature Sensor at 5 or 10 meters

Optional parameters recorded at various sites are as follows:

- All Colorado and Nebraska stations: LiCor #LI-200SA Pyranometer and NRG grounding kit (4 ft. lightning spike and 8 ft. ground rod)
- All Nebraska stations: Additional temperature sensor installed at 40 meters
- Sites 101, 105, and 108 in Nebraska: These sites utilize an existing radio tower, an extra calibrated anemometer was installed at 50 meters.

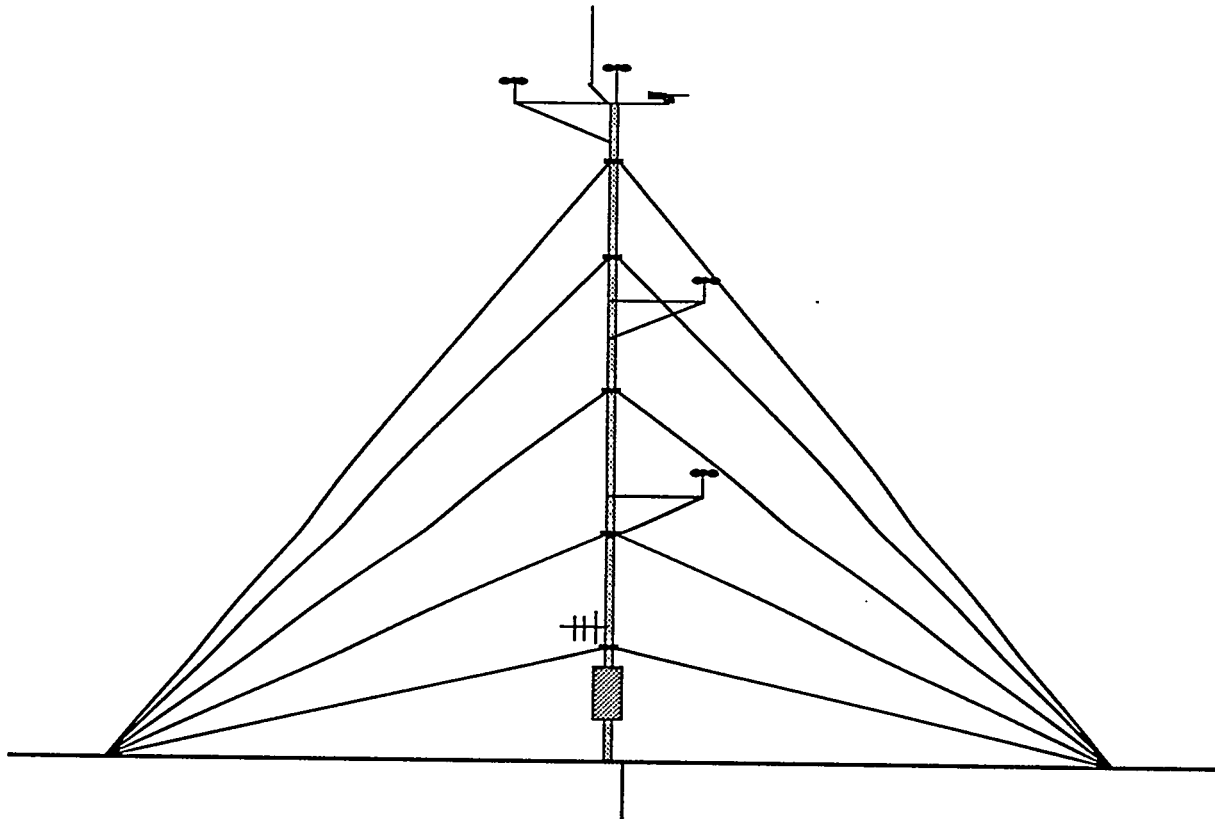


FIGURE 1. MONITORING STATION CONFIGURATION

DATA ANALYSIS AND RECOVERY RATES

All data is quality checked by GEC and erroneous data is removed. Data is considered erroneous if it does not appear to be representative of the actual wind conditions. Missing or removed data from the Colorado stations are left blank. All wind speed data are replaced in the Nebraska program to provide a complete data set for analysis. If only a few hours of data are missing, the data is replaced with the average of the hour before and after. For a greater portion of missing data, data replacement is based on a

WIND SPEED

The average wind speeds at 40 meters range from 6.5 – 7.4 m/s (14.5 – 16.5 mph) in Nebraska and 7.6 – 8.9 m/s (17.0 – 19.9 mph) in Colorado. Figure 3 provides average wind speeds for the individual stations in Colorado and Nebraska. The average wind speeds in Colorado are significantly higher than Nebraska. This may be in part due to the fact that the average elevation for the Colorado stations is 900 meters higher than the Nebraska stations. Also, several of the Colorado station averages are based on less than a year of data.

Figures 4 and 5 provide seasonal wind speed patterns for Colorado and Nebraska respectively. Preliminary data shows that the winds in both Colorado and Nebraska are lowest in the summer months (June to August) and highest in the fall and spring. The seasonal pattern for Colorado is incomplete as a complete year of data has not been collected from all stations.

Diurnal wind speed patterns are provided in Figures 6 and 7. The Nebraska stations all follow a similar pattern with high winds in the late afternoon and low winds in the morning. The diurnal patterns for the Colorado stations are not as consistent as in Nebraska; however, it does appear that the wind speeds are slightly higher at night for most stations.

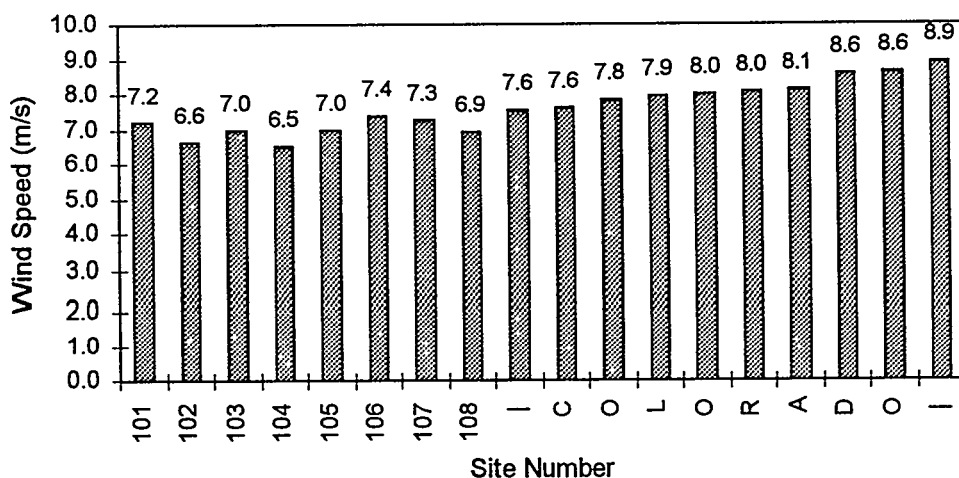


FIGURE 3. AVERAGE WIND SPEEDS AT 40 METERS

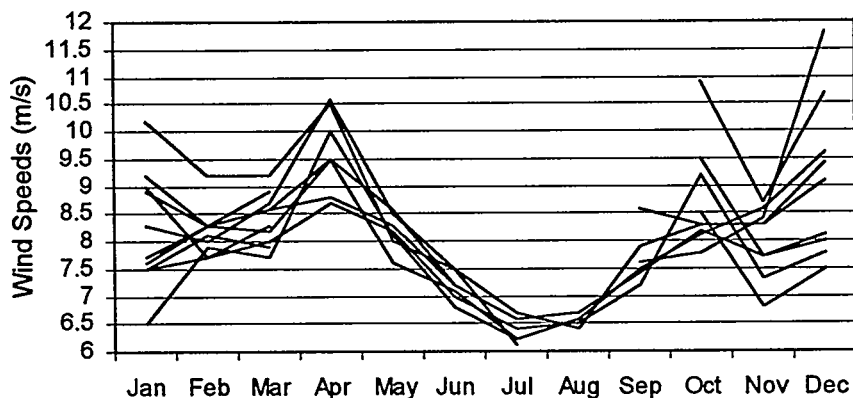


FIGURE 4. SEASONAL WIND SPEED PATTERNS IN COLORADO

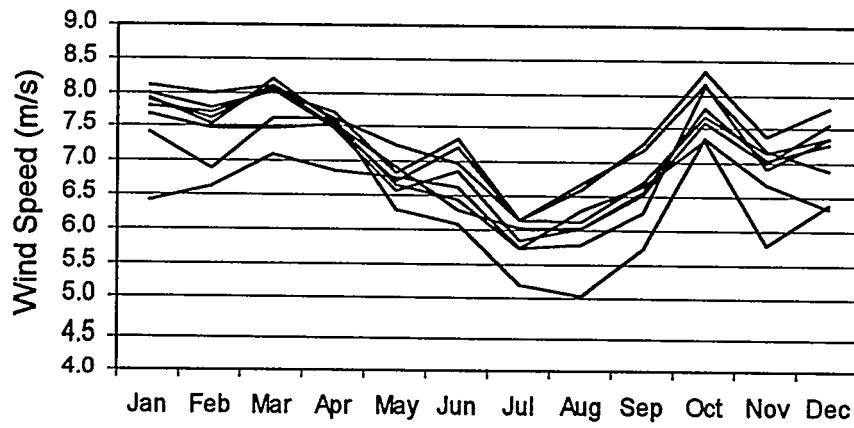


FIGURE 5. SEASONAL WIND SPEED PATTERNS IN NEBRASKA

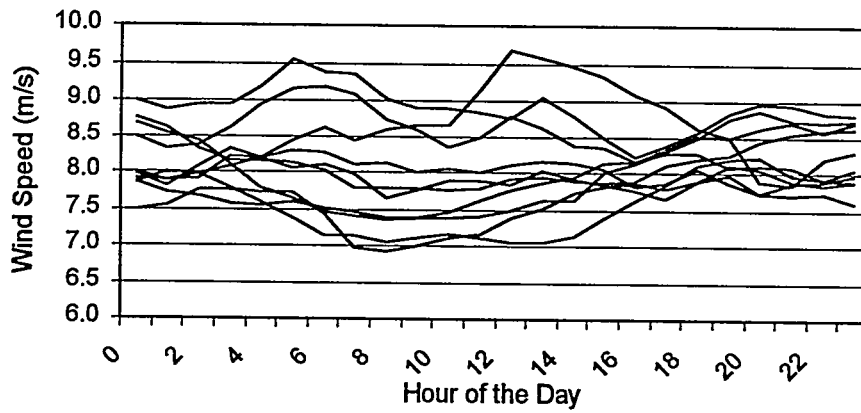


FIGURE 6. DIURNAL WIND SPEEDS IN COLORADO

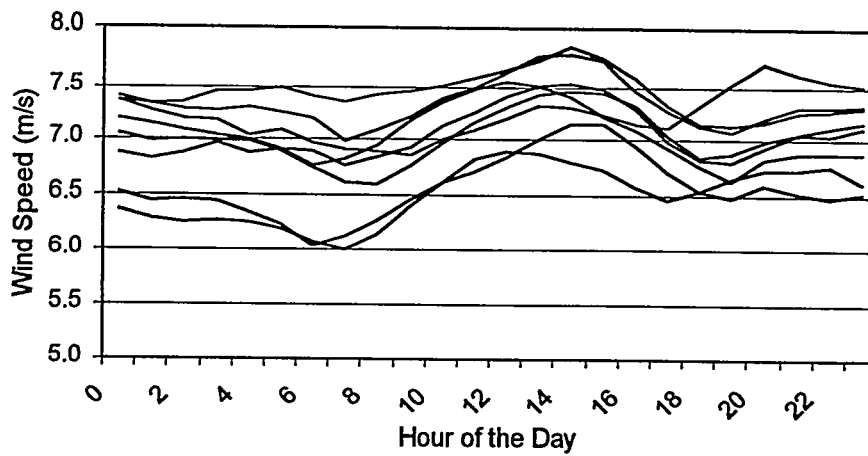


FIGURE 7. DIURNAL WIND SPEEDS IN NEBRASKA

WIND DIRECTION

On an annual basis, the energy-producing winds in Nebraska are predominantly from the northwest. During the low wind, summer months the predominant direction shifts to the south-southeast.

Preliminary data in Colorado show the wind directions to be more variable than Nebraska both by season and location. The topography of the Colorado sites is also more complex and is one contributing factor to the direction variations. At the four northern sites the winds are from the northwest for most of the year. At the two east-central sites, the winds are from the north-northwest between the months of October to April and from the south-southeast during the summer months (May to September). The one site located at the center of the state experiences winds consistently from the northeast all year. The three sites in the southern portion of the state have winds from the south-southeast most of the year with winds from the southwest in the winter months of October through January.

TURBULENCE INTENSITY

All stations in Colorado and Nebraska experience moderate turbulence intensity (TI) values which indicate no significant concerns for wind energy development. The average TI values for each station are presented in Table 1. These values are for the predominant wind direction only.

WIND SHEAR

Wind shear exponent values between 25 and 40 meters for power producing wind speeds above 4 m/s (9 mph) are provided in Table 1. Although there is some variation, the wind shear values at most of the sites in Nebraska and Colorado are fairly high.

TABLE 1. TURBULENCE INTENSITY AND WIND SHEAR EXPONENTS

NEBRASKA			COLORADO		
SITE	TI	SHEAR	SITE	TI	SHEAR
101-Imperial	0.14	0.16	201	0.14	0.19
102-Rushville	0.15	0.28	202	0.13	0.22
103-Winnebago	0.13	0.24	203	0.14	0.23
104-Wahoo	0.15	0.27	204	0.13	0.18
105-Kimball	0.15	0.28	205	0.13	0.28
106-Valentine	0.13	0.18	206	0.12	0.17
107-Springview	0.13	0.25	207	0.13	0.18
108-Stuart	0.14	0.25	208	0.13	0.18
			209	0.12	0.14
			210	0.14	0.10

FREQUENCY DISTRIBUTIONS

Frequency distributions for Colorado and Nebraska are provided in Figures 7 and 8. The frequency distributions provided in Figure 7 are for the four Colorado stations which have a complete year of data. Nebraska totals are based on an annual average for two complete years of data. Also note that the Colorado stations do not have missing or removed data replaced; therefore, the annual totals are slightly less than in Nebraska where all wind speed data is replaced.

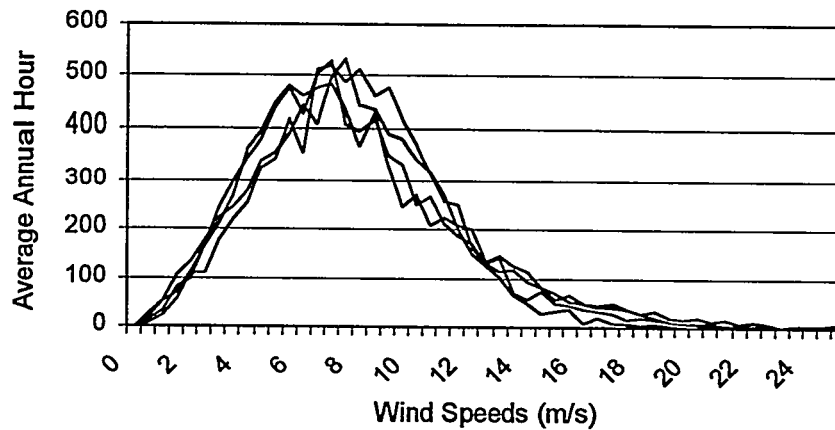


FIGURE 7. FREQUENCY DISTRIBUTIONS IN COLORADO

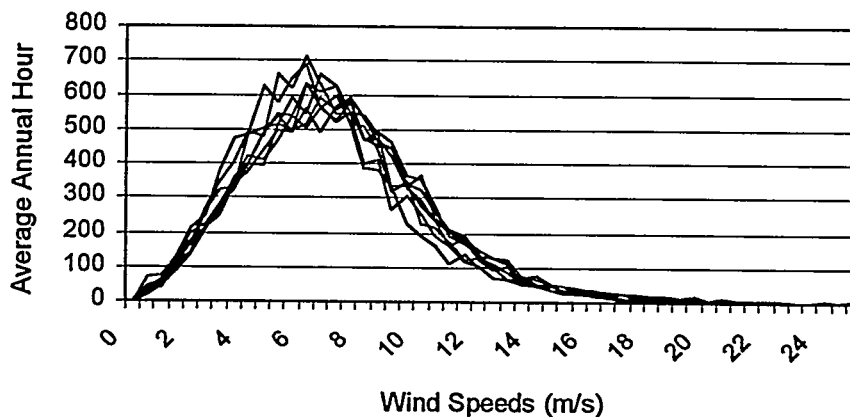


FIGURE 8. FREQUENCY DISTRIBUTIONS IN NEBRASKA

ACKNOWLEDGEMENTS

GEC would like to thank the members of the Nebraska Wind Energy Task Force, Public Service Company of Colorado and all Colorado utilities participating in U*WRAP, and Tucson Electric Power for the opportunity to present this information. GEC would also like to thank the University of Nebraska High Plains Climate Center, Zond Development Corporation Midwest Regional Office, and Air Resource Specialists for their maintenance support in Nebraska and Colorado as well as NRG Systems for their maintenance support and equipment troubleshooting throughout the U*WRAP programs.

**A GIS WIND RESOURCE MAP
WITH TABULAR PRINTOUT OF MONTHLY AND ANNUAL WIND SPEEDS
FOR 2,000 TOWNS IN IOWA**

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ABSTRACT

The Iowa Wind Energy Institute, under a grant from the Iowa Energy Center, undertook in 1994 to map wind resources in Iowa. Fifty-meter met towers were erected at 13 locations across the state deemed promising for utility-scale wind farm development. Two years of summarized wind speed, direction, and temperature data were used to create wind resource maps incorporating effects of elevation, relative exposure, terrain roughness, and ground cover. Maps were produced predicting long-term mean monthly and annual wind speeds on a one-kilometer grid. The estimated absolute standard error in the predicted annual average wind speeds at unobstructed locations is 9 percent. The relative standard error between points on the annual map is estimated to be 3 percent. These maps and tabular data for 2,000 cities and towns in Iowa data are now available on the Iowa Energy Center's web site (<http://www.energy.iastate.edu>).

BACKGROUND

Until recently the most authoritative source of wind resource estimates in Iowa was the *Wind Energy Resource Atlas of the United States*.¹ The maps in this report show that winds, on average, are strongest in the northwestern corner of the state and diminish steadily towards the south and east. The annual average wind power density is estimated to be Class 4 (400-500 W/m² at 50 meters tower height) in the northwest, Class 3 (300-400 W/m²) in a wide band across the middle, and Class 2 (200-300 W/m²) in the southeast.² These estimates are based largely on data collected from the 1950s to 1970s at around a dozen wind monitoring stations across the state, most of them located at airports.

In 1993, the Union of Concerned Scientists published a map of wind resources in Iowa in which a geographical information system (GIS) was used to refine wind speed estimates to reflect local terrain and vegetation characteristics.³ Although this map provided a good deal more geographic detail than the

¹ D. L. Elliott et al., *Wind Energy Resource Atlas of the United States* (Golden, Colo.: National Renewable Energy Laboratory, 1987), p. 57.

² The wind classification strongly affects the economic attractiveness of wind power development. Generally speaking, Class 4 and 5 areas are presently the focus of large-scale wind power development in the United States and worldwide, but development may occur in Class 3 areas in the near future with advances in wind energy conversion technology.

³ Michael C. Brower, et al., *Powering the Midwest: Renewable Energy for the Economy and the Environment* (Cambridge, Mass.: Union of Concerned Scientists, 1993).

wind atlas, it did not present a fundamentally new interpretation of Iowa wind resources since it used the atlas as its starting point. The UCS method assumed that the atlas designations accurately represent average wind speeds over large areas. Using digital terrain elevation and vegetation cover data, UCS then adjusted these wind classes to account for the estimated effects of local conditions. A disadvantage of the UCS approach is that it relied on an assumed relationship between wind speed, terrain exposure, and surface roughness that may not reflect conditions on the ground. In addition, the use of the wind atlas—which assigned regions to broad wind classes—creates abrupt transitions between areas on the map.

WIND DATA AND ADJUSTMENTS

The wind measurement program initiated by the Iowa Wind Energy Institute (IWEI) has provided a valuable opportunity to confirm and refine the wind speed estimates published in the national wind atlas and the UCS map. In the early 1990s, the IWEI mounted anemometers on 13 tall towers at locations across the state deemed promising for utility-scale wind farm development. The UCS map was used as a guide in helping to select the sites. All are on well-exposed ground near the tops of ridges and hills with few nearby obstructions such as trees or buildings. Two full years of data (from June 1994 to May 1996) were collected and summarized from 12 of these sites, while a year of data (from June 1995 to May 1996) was available from the thirteenth site, Muscatine. Figure 1 shows the locations of these sites. Collectively these data represent the best publicly available source of information on Iowa wind resources and a good basis from which to develop new Iowa wind maps.

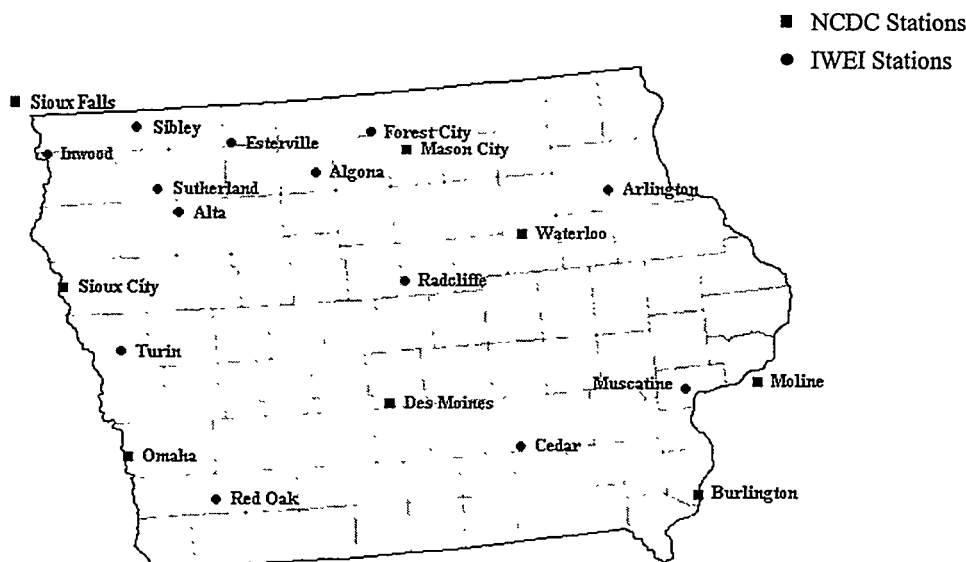


FIGURE 1. Locations of Anemometer Stations

Wind Data

Table 1 lists summary data on the 13 stations monitored by the Iowa Wind Energy Institute.⁴ The observed wind power densities for the measurements were about one wind class lower than those depicted in the national wind atlas. The geographic distribution, however, is similar. Most stations located in the northwestern part of the state recorded Class 3 winds. The two exceptions were Estherville (Class 4) and Inwood (Class 2). Stations located in the east and south, including Muscatine, Arlington, Cedar, Turin, and Red Oak, recorded Class 2 wind speeds. Radcliffe, in the middle of the state, recorded unexpectedly strong winds that gave it the second highest average wind power density in the group after Estherville and virtually tied with Alta. The monthly mean wind speeds shown in Table 2 indicate that winds tend to be stronger in winter and spring than in summer and fall.

In addition to the 13 IWEI sites, data from 8 National Climatic Data Center (NCDC) sites in Iowa and bordering parts of South Dakota, Nebraska, and Illinois (shown in Figure 1) were used in the analysis. The selected sites had been continuously monitored for an extended period since 1965, with only minor changes in anemometer height and location. The data from these sites served two purposes. First, they increased the number of independent measurements used to generate the GIS maps. This was especially important because, unlike the IWEI sites, the NCDC sites are in low-lying locations. Including these sites therefore increases the diversity of site conditions and presumably improves the overall accuracy of the final map. Second, three of the sites (Des Moines, Waterloo, and Sioux City) were used to adjust wind speeds measured at the IWEI sites to a long-term climate norm defined as 1965-1990.

TABLE 1. IWEI Station Summary

ID	Name	Longitude (Decimal)	Latitude (Decimal)	Shear Expo- nent	Annual Average Speed* (m/s)	Average Power Density** (W/m ²)	Wind Class
11	Radcliffe	93.44 W	42.30 N	0.19	7.37	397	3
22	Turin	95.91 W	41.97 N	0.27	6.51	248	2
33	Algona	94.14 W	43.04 N	0.21	7.15	366	3
77	Muscatine	91.11 W	41.45 N	0.19	6.06***	225	2
100	Cedar	92.57 W	41.19 N	0.18	6.10	214	2
200	Inwood	96.47 W	43.25 N	0.19	6.81	279	2
300	Sutherland	95.52 W	43.00 N	0.20	7.21	348	3
400	Alta	95.34 W	42.84 N	0.17	7.56	395	3
500	Sibley	95.68 W	43.40 N	0.22	7.40	375	3
600	Estherville	94.86 W	43.27 N	0.16	7.94	431	4
700	Forest City	93.63 W	43.28 N	0.22	6.92	306	3
800	Arlington	91.61 W	42.77 N	0.25	6.30	243	2
900	Red Oak	95.17 W	41.00 N	0.18	6.69	294	2

*Projected to 50 m tower height from 48.8 m using the measured wind shear exponent between 33 and 48.8 m and adjusted for tower shadowing. **Calculated using hourly data and temperature- and elevation-corrected air densities. ***From June 1995 to May 1996; data for other stations are from June 1994 to May 1996..

⁴ The IWEI wind speed data were validated and adjusted according to standard procedures to correct for icing, tower shadowing, and failed sensors, data loggers, and towers. Tower shadowing was eliminated by taking the maximum speed recorded at opposing anemometers at the 48.8 m (160 ft) height depending on the wind direction.

TABLE 2. Mean wind speeds recorded at IWEI sites (m/s)*

	Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Radcliffe	7.4	8.1	8.7	8.0	8.2	7.3	6.3	5.5	5.6	6.8	7.8	8.5	7.1
Turin	6.5	6.7	6.9	7.0	7.0	5.7	5.9	5.2	5.8	6.4	7.1	7.3	6.6
Algona	7.2	7.8	8.0	7.5	7.7	6.8	6.5	6.4	5.5	6.0	7.4	8.4	7.3
Muscatine	6.1	6.7	7.3	7.0	7.3	5.9	4.5	4.8	4.0	5.3	6.7	6.6	6.3
Cedar	6.1	6.5	6.9	6.8	7.6	6.3	5.1	4.8	4.6	5.2	6.4	6.8	5.9
Inwood	6.8	7.3	7.3	7.3	7.4	6.8	6.1	5.6	5.3	6.5	7.4	7.7	6.5
Sutherland	7.2	7.4	8.2	7.8	7.8	7.3	6.7	5.9	5.6	6.5	7.9	8.2	6.9
Alta	7.6	7.5	8.4	8.1	8.1	7.3	6.9	6.2	6.2	7.0	8.2	8.5	7.7
Sibley	7.4	7.8	8.9	8.2	7.7	6.9	6.8	6.0	5.7	6.6	7.9	8.0	7.8
Estherville	7.9	8.3	9.3	8.3	8.4	7.4	7.1	6.6	6.1	7.6	8.9	9.0	8.0
Forest City	6.9	7.5	7.9	7.6	7.2	6.6	5.8	5.9	5.5	6.2	7.4	7.8	7.2
Arlington	6.3	6.6	7.2	6.9	6.9	6.0	5.5	5.2	5.1	5.5	6.9	7.1	6.3
Red Oak	6.7	6.7	7.3	7.6	7.8	6.0	6.0	5.4	5.5	6.4	7.0	7.6	6.6

*Period June 1994 to May 1996, except Muscatine, June 1995 to May 1996. Adjusted for tower shadowing. Projected to 50 m tower height.

Table 3 summarizes the monthly and annual average data at the 8 NCDC sites for two time periods: June 1994 to May 1996, and 1965 to 1990 (1978 for Burlington).⁵ The expected seasonal variation in wind speed is readily observed. In addition, the data suggest that winds in the 1994-96 period were somewhat lower than the norm, especially in the eastern part of the state. This may account for the relatively low wind power densities observed at the IWEI sites compared with the atlas predictions.

Height Adjustments

The IWEI site data, taken at 48.8 m above ground level, required only minor adjustment to match the nominal tower height of 50 meters. The NCDC data required substantial adjustment, however, since all of these measurements were taken at a height of less than 10 meters. The challenge was to determine an appropriate value to use for the shear exponent, α , in the power-law equation. The shear exponents recorded at the IWEI sites between 10 and 50 meters height ranged from 0.16 to 0.27 over all sites and months, with an average of 0.21. The mean value, however, was strongly affected by two high values from stations situated in fairly hilly terrain. Excluding these two points, the average shear exponent for the IWEI sites is 0.19. Considering that most airport anemometers are located on runways that are very flat and covered with asphalt or short grass, we adopted a slightly lower average shear exponent of 0.18 for the NCDC sites. In addition, to reflect the typical seasonal variation of surface roughness, we allowed the exponent for the NCDC sites to vary in direct proportion to a 3-month running average of the coefficients observed at Estherville and Alta. This resulted in a minimum shear exponent of 0.16 from February to May and a maximum of 0.21 in August and September.

⁵ Data for 6 of the 8 NCDC sites were provided by Iowa State Climatologist Harry Hillicher of the Iowa Department of Agriculture. Data for Burlington were taken from the national wind atlas (and therefore only cover the period 1965 to 1978), while data for Mason City were taken from the *Solar and Meteorological Surface Observation Network 1961-1990* CD-ROM, available from the National Climatic Data Center in Asheville, North Carolina.

TABLE 3. Mean wind speeds at NCDC sites (m/s)

Station	Ht. (m)	Period	Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Waterloo	6.1	1994-96	4.4	5.0	5.4	5.0	5.4	4.6	3.9	3.4	3.1	3.4	4.5	5.1	4.3
		1965-90	4.8	5.3	5.2	5.6	5.7	4.9	4.5	3.9	3.8	4.1	4.6	5.0	5.1
Sioux Falls	5.2	1994-96	4.9	5.1	5.3	5.3	5.5	4.8	4.7	4.4	4.4	4.5	5.2	5.2	4.5
		1965-90	5.0	4.9	5.0	5.5	5.9	5.3	4.8	4.4	4.4	4.6	4.8	5.1	4.8
Sioux City	7.3	1994-96	5.0	5.3	5.3	5.5	5.5	4.9	4.7	4.1	4.2	4.6	5.5	5.7	4.6
		1965-90	5.0	5.2	5.1	5.7	5.9	5.3	4.8	4.2	4.1	4.4	4.8	5.0	5.0
Omaha	6.1	1994-96	4.6	5.4	5.5	5.5	5.4	4.3	4.0	3.4	3.3	4.0	3.9	5.4	4.9
		1965-90	4.4	4.7	4.7	5.1	5.2	4.4	4.1	3.8	3.7	3.9	4.1	4.5	4.5
Moline	7.6	1994-96	3.6	4.1	4.2	4.3	4.7	3.8	2.6	2.8	2.5	2.9	3.6	4.0	3.5
		1965-90	4.5	5.1	4.9	5.4	5.4	4.6	4.2	3.6	3.4	3.7	4.4	4.9	4.9
Des Moines	6.1	1994-96	4.4	4.9	5.1	5.2	5.5	4.5	3.8	3.5	3.4	3.6	4.7	5.1	4.2
		1965-90	4.7	5.2	5.1	5.5	5.5	4.8	4.4	4.0	3.8	4.1	4.5	4.8	4.9
Burlington	6.1	1994-96	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		1965-78	4.5	5.0	5.0	5.0	5.0	5.0	3.7	3.7	3.7	4.1	4.1	4.1	5.0
Mason City	6.1	1994-96	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
		1965-90	5.0	5.9	5.0	5.8	5.8	5.2	4.8	3.9	3.8	4.2	4.9	5.3	5.5

Climatological Adjustments

Since the goal of this project was to estimate long-term average wind speeds, it was necessary to make adjustments in the measured wind speeds at the IWEI sites to approximate the long-term climate norm. Using just one control site to establish a baseline record—the usual practice—was not adequate for this project because the IWEI sites are scattered widely around the state. Instead, we calculated linear regression coefficients relating the monthly wind speed measurements at the IWEI sites to monthly measurements at three representative NCDC sites, Des Moines, Waterloo, and Sioux City. These coefficients were then multiplied by the deviations between the short-term and long-term monthly averages at the NCDC sites to arrive at adjusted monthly averages at the IWEI sites. The resulting adjustments ranged from +0 to +2 percent in the northwestern portion of the state to +2 to +5 percent in the eastern and southern portions. The r^2 coefficients of the regressions range from 67 percent to 95 percent, with the bulk falling between 80 and 90 percent, indicating that deviations from the monthly norms at the control sites are a very good predictor of variations at the IWEI sites.

Adjusted Wind Data and Uncertainties

Table 4 shows the adjusted data used in the analysis, which were arrived at by multiplying the wind speeds in Tables 2 and 3 by the estimated height and climatological adjustment factors. The overall uncertainty in these figures is estimated by combining the individual sources of potential error under the assumption that they are statistically independent of one another. In addition to the uncertainties in the height and climatological adjustments mentioned previously, there is a measurement uncertainty of approximately 5 percent associated with all of the monthly and annual average data. (This does not include possible discrepancies between the NCDC and IWEI data because of the different anemometer equipment used.) The combined standard error in the annual mean speeds is about 7 percent for the IWEI sites (7.9 percent for Muscatine because of its shorter period of record), while the error in the monthly means is 9.1 percent (11.4 percent for Muscatine). The standard errors in the monthly and annual means for the NCDC sites range from 7.5 to 8.4 percent for both monthly and annual means.

TABLE 4. Adjusted mean wind speeds (m/s)

	Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Waterloo	7.01	7.52	7.37	7.77	7.85	6.91	6.59	5.90	5.97	6.36	7.00	7.39	7.31
Sioux Falls	7.44	7.16	7.23	7.88	8.32	7.61	7.19	6.91	7.09	7.40	7.48	7.85	7.11
Sioux City	6.96	7.14	7.00	7.59	7.94	7.15	6.71	6.18	6.19	6.52	6.98	7.06	6.93
Omaha	6.40	6.60	6.60	7.13	7.19	6.23	5.99	5.74	5.72	6.06	6.26	6.60	6.52
Moline	6.37	7.01	6.76	7.29	7.24	6.22	5.90	5.19	5.01	5.49	6.34	6.91	6.80
Des Moines	6.88	7.38	7.17	7.64	7.61	6.69	6.50	6.04	5.99	6.36	6.82	7.13	7.02
Burlington	6.57	7.09	7.09	6.93	6.93	7.03	5.41	5.65	5.79	6.37	6.22	6.08	7.23
Mason City	7.35	8.29	7.85	8.04	8.03	7.32	6.99	6.02	5.91	6.46	7.42	7.87	7.93
Radcliffe	7.69	8.47	8.51	8.58	8.46	7.82	7.07	6.12	6.25	7.41	7.54	8.04	8.05
Turin	6.48	6.74	6.78	7.11	7.22	6.05	6.11	5.39	5.81	6.36	6.44	6.64	7.08
Algona	7.37	8.10	7.82	7.90	8.00	7.24	7.00	6.84	5.98	6.41	7.15	7.97	8.02
Muscatine	6.34	7.12	7.36	7.23	7.28	6.11	5.90	5.50	4.98	5.54	5.92	6.15	6.99
Cedar	6.37	6.82	6.75	7.27	7.82	6.70	5.74	5.28	5.13	5.68	6.08	6.37	6.80
Inwood	6.84	7.38	7.18	7.64	7.69	7.24	6.47	5.86	5.49	6.56	6.67	6.93	7.14
Sutherland	7.28	7.50	7.94	8.10	8.21	7.82	6.98	6.20	5.79	6.55	7.23	7.42	7.58
Alta	7.61	7.64	8.23	8.31	8.44	7.78	7.23	6.50	6.35	7.07	7.59	7.82	8.37
Sibley	7.56	7.99	8.68	8.57	8.06	7.36	7.24	6.32	6.07	6.90	7.48	7.47	8.60
Estherville	8.08	8.46	9.07	8.68	8.90	7.88	7.43	6.90	6.42	7.75	8.36	8.31	8.76
Forest City	7.08	7.66	7.69	7.99	7.50	7.01	6.23	6.24	5.92	6.53	7.04	7.32	7.86
Arlington	6.48	6.82	7.05	7.28	7.21	6.36	5.94	5.55	5.53	5.79	6.62	6.65	6.96
Red Oak	6.70	6.77	7.13	7.75	8.12	6.46	6.26	5.66	5.66	6.41	6.18	6.75	7.22

MAPPING TECHNIQUE

The basic mapping technique was to fit the adjusted wind speed data observed at the 21 NCDC and IWEI sites to three parameters: elevation, terrain exposure, and terrain roughness associated with land form. Subsequently the maps were adjusted for the estimated effects of surface roughness due to land cover. We arrived at this technique after much trial and error involving different combinations of possible input parameters.⁶ The quality of the fit in most cases was reasonably high. The r^2 coefficient for the regression on the annual wind data was 84 percent, indicating that the three parameters explain the great majority of wind speed variations observed at the 21 sites. The r^2 coefficients for the monthly wind maps were generally lower, ranging from 45 to 85 percent and averaging 72 percent, reflecting the greater variation and larger uncertainties associated with the monthly data. Further details of the method and data sources are provided below.

Elevation

Terrain elevation was by far the most significant determinant of wind speed in our regression analyses, with a solitary r^2 coefficient in the fit to the annual data of 51 percent. This is not surprising considering that the state is relatively flat, so that wind speeds are not greatly affected by the presence of hills, ridges, and other features of complex terrain. In addition, mean upper air wind speeds do not vary greatly across the state. Sampled digital elevation data were extracted from the US Geological Survey's *Conterminous US AVHRR Companion Disc*, a CD-ROM available from the EROS Data Center in Sioux Falls, South

⁶ Other parameters that were tried include surface roughness due to land cover, geographic position (latitude and longitude), upper air wind speeds, and various methods of weighting average elevation and surface roughness for wind direction. Ridge orientation and slope were not considered as we believe the data are not adequate to identify a ridge effect independent of exposure. However, this could be the subject of further investigation.

Dakota. On this map, Iowa's elevation ranges from about 150 m (492 ft) in the Missouri River basin to 500 m (1,640 ft) at the northwest border with Minnesota.

Terrain Roughness

It was observed early in the analysis that certain IWEI sites had higher wind shear exponents and lower wind speeds than others. The two most prominent examples are Turin and Arlington. The higher shear coefficients appeared to be associated with the presence of more rolling or undulating terrain than usual. We therefore set out to create a map of terrain roughness that could capture this effect in the regression fit. First, we applied a high-pass filter to the elevation data. This filter subtracts the average elevation of the 8 pixels surrounding each pixel from the elevation of the central pixel. Next we squared the image to convert negative to positive values and normalized it to the maximum to obtain a non-dimensional roughness parameter. Then we averaged this parameter over a distance of 26 km and finally took the square root of the result to arrive at a map of root-mean-square relative terrain roughness. This non-dimensional measure of roughness turned out to be correlated with measured wind speeds at the IWEI sites and significantly improved the overall quality of the regression fit. The solitary r^2 coefficient in the fit to the annual data was 32 percent.

Terrain Exposure

In theory, an important ingredient in the estimation of wind speeds is the exposure of a site to the wind. To calculate this it is necessary to compare the elevation of each point on the map with some measure of the elevation of points in the immediately surrounding area. For this study we defined this surrounding reference area to be a square measuring 26 kilometers on a side, an intermediate scale length that reveals

important details of land form without obscuring long-distance trends in elevation.

TABLE 5. Extracted elevation, exposure, and terrain roughness

	Elevation (m)	Exposure (m)	Non- Dimensional Roughness
Waterloo	257	-18	0.05
Sioux Falls	439	4	0.07
Sioux City	329	-15	0.08
Omaha	297	-32	0.11
Moline	177	-30	0.06
Des Moines	287	24	0.08
Burlington	195	9	0.05
Mason City	357	-3	0.03
Radcliffe	366	29	0.04
Turin	403	33	0.12
Algona	366	14	0.03
Muscatine	223	32	0.07
Cedar	256	17	0.08
Inwood	442	32	0.08
Sutherland	464	35	0.09
Alta	473	46	0.07
Sibley	490	23	0.04
Estherville	465	58	0.04
Forest City	385	6	0.04
Arlington	366	43	0.13
Red Oak	385	33	0.10

In the subsequent analysis we found that terrain exposure is much less strongly associated with the observed wind speeds than is elevation or terrain roughness—the solitary r^2 coefficient in the fit to the annual data was just 8 percent—an indication that Iowa's hills and ridges are so low that the wind accelerates very little over them. Nevertheless, the estimated regression coefficients were statistically significant in some cases, and hence this parameter was retained in the fit.

Regression

Once the maps representing elevation, exposure, and terrain roughness were created, we extracted values from each map for the 21 monitoring stations. The values shown in Table 5 became the independent variables in the general linear least-squares regression model. The wind speeds in Table 4 were the dependent variables.

The results of the 13 regressions performed (one for each month and one for the year) are shown in Table

TABLE 6. Regression coefficients and quality of fit

Month	ANN	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Intercept	6.39	7.79	7.33	7.21	7.16	6.39	5.35	5.10	4.69	5.25	6.01	6.40	7.27
Expo	0.0010	0.0045	0.0086	0.0017	0.0019	0.0009	-0.0034	-0.0023	-0.0046	-0.0002	-0.0021	-0.0044	0.0075
Elev	0.0037	0.0018	0.0029	0.0035	0.0032	0.0039	0.0052	0.0040	0.0040	0.0047	0.0047	0.0047	0.0029
RMS Hpass	-10.15	-15.35	-14.37	-9.69	-7.08	-11.36	-8.32	-7.13	-2.80	-6.35	-10.21	-11.33	-13.91
Std Err	0.22	0.26	0.30	0.23	0.33	0.35	0.28	0.32	0.39	0.38	0.36	0.38	0.26
r^2	84.4%	82.1%	83.4%	82.0%	63.9%	69.5%	79.3%	65.8%	45.3%	64.4%	71.9%	70.0%	85.1%

6. The table shows the r^2 coefficient signifying the overall quality of the fit and the standard error in the predictions. The standard error provides an indication of the likelihood that the map estimate deviates from the true long-term wind speed by a certain amount, assuming no systematic biases in the data. If the data are normally distributed, then errors of one standard error or less occur approximately 68 percent of the time; errors of two standard errors or less occur approximately 95 percent of the time.

Several observations can be made about these results. First, the coefficient for exposure is consistently positive in the winter and negative in the summer. This suggests—if the height and climatological adjustments are valid—that low-lying areas of the state (such as river valleys) are better shielded from winds in the winter than in the summer. The physical explanation may be that cold winter air tends to settle in valleys and become thermally disconnected from air at higher elevations. The seasonal variation in the roughness coefficient may reflect the same physical phenomenon. This finding is sensitive to the seasonal variation in the wind shear exponent for the NCDC sites, however.

Second, the negative roughness coefficient, as expected, tends to reduce predicted wind speeds in hilly areas. The effect appears to be quite strong; without it, the predicted annual average wind speed in Turin would be as much as 1 m/s higher. In fact, the effect may be too large for very hilly terrain such as that seen in northeastern Iowa and southwestern Wisconsin, where the non-dimensional roughness parameter reaches a value of more than 0.2. However, aside from Arlington, which lies at the edge of this region, no data are available in such areas to determine the true magnitude of this effect.

Third, the standard error in the predicted annual average wind speeds, 0.22 m/s, represents a relative error of just 3 percent. It is important to recognize, however, that this measure of error reflects only the random uncertainties in the original data such as might arise from anemometer errors or local climate anomalies. There may also be systematic biases in the data (i.e., errors that affect several stations with the same direction and magnitude), stemming particularly from the height and climatological adjustments, that increase the overall error margin. Taking this possibility into account, we estimate that the standard error in the predicted annual average wind speed is 9 percent, while for the predicted monthly average wind speed it is 12 percent.

Surface Roughness

In the early stages of the analysis we expected that surface roughness—due to vegetation and other types of land cover, not terrain roughness due to land form—would be a significant determinant of wind speeds at the 21 IWEI sites. This turned out not to be the case, however. One reason may be limitations in the land cover data, which like the terrain data are at a relative coarse resolution of 1 km. In addition, nearly all of the sites are located in areas of relatively low surface roughness, so in hindsight one might have predicted that little association with surface roughness would be observed.

Nevertheless, since it is well known that surface roughness affects local wind speeds, we decided to use a measure of roughness to adjust the wind speeds on the maps after the regression fit was completed. First, digitized classifications of crops and natural vegetation for Colorado were obtained from the

Conterminous US Land Cover Characteristics Data Set 1990 Prototype CD-ROM, distributed by the USGS EROS Data Center. This data set has the same resolution and is in the same projection as the digital elevation model we used. The 21 land cover types were regrouped into five summary classes: forest, woodlands, mixed woodland/cropland, cropland/grassland, and water. Then a map of urban or built-up areas obtained from the *Conterminous US AVHRR Companion Disc* CD-ROM was overlaid.

The land cover classes were then assigned the following roughness lengths: forests 0.8 m, woodlands and urban areas 0.4 m, mixed woodland-cropland 0.1 m, cropland 0.03 m, and water 0.0002 m. The assigned roughness values, other than that of water, are appropriate mainly for summer conditions, and will tend to be lower in winter when leaves have fallen, tall grasses and crops are absent, and the ground is covered with snow. Since boundary layer theory indicates that the wind speed adjustment should depend on the logarithm of the surface roughness, we created a new map of the logarithm of the assigned roughness lengths. Then we calculated a distance-weighted average logarithm around each pixel on the map. The weighting, which was proportional to the reciprocal of the distance squared, was intended to reflect the relatively short range of the influence of roughness changes on wind speed. Weights were also applied to reflect the proportion of energy coming from different compass directions. Lastly, we normalized this map to what we assumed to be "typical" conditions at the IWEI and NCDC sites by subtracting the logarithm of the roughness length for cropland, 0.03 m. The result was a map depicting deviations in the weighted average logarithm of surface roughness from the norm. For example, a large forested area would be assigned a value of $\log(0.8) - \log(0.03) = 3.28$; a large lake would be assigned a value of $\log(0.0002) - \log(0.03) = -5.01$.

The last step was to derive a wind speed adjustment that depended on the deviation in weighted average logarithm of the surface roughness. Assuming that the wind speed at the top of the near-surface boundary layer is unaffected by roughness changes, and expanding the observed relationship between wind speed and height in a stable atmosphere, the resulting wind speed adjustment ranged from +6 percent for significant expanses of water to -5.5 percent for significant expanses of forest.

RESULTS AND DISCUSSION

The maps produced in this project are available to be viewed on the Iowa Energy Center's Web site at <http://www.energy.iastate.edu>. Monthly and annual mean wind speeds for 2,000 Iowa towns have also been extracted in tabular format, along with the predicted maximum annual mean wind speed within an 8 kilometer (5 mile) radius of each town. When converted to wind power density using typical frequency distributions derived from the IWEI sites, the predicted wind classes conform closely with those depicted in the wind atlas.

The predicted and measured (extrapolated and adjusted) annual mean wind speeds are compared in Figure 2. The error bars represent the standard error in the regression of 0.22 m/s, and therefore do not include any systematic errors in the measurements themselves, which may be considerably larger. Two points fall significantly above the line of equality, Sibley and Inwood, indicating that the map overpredicts wind speeds at these two locations. Perhaps not coincidentally, the sites are adjacent to one another in the northwest corner of the state, suggesting there may be an error in the climatological adjustment in this area or some other factor that reduces wind speeds there. On the other hand, the map significantly underpredicts wind speeds at Estherville and Radcliffe. The discrepancies are consistent with normal statistical behavior of uncertain measurements, however, and may therefore also be due merely to measurement error.

This project has provided updated maps of monthly and annual average wind speeds in Iowa using recent data from 13 anemometers on tall towers distributed around the state as well as long-term data from 8

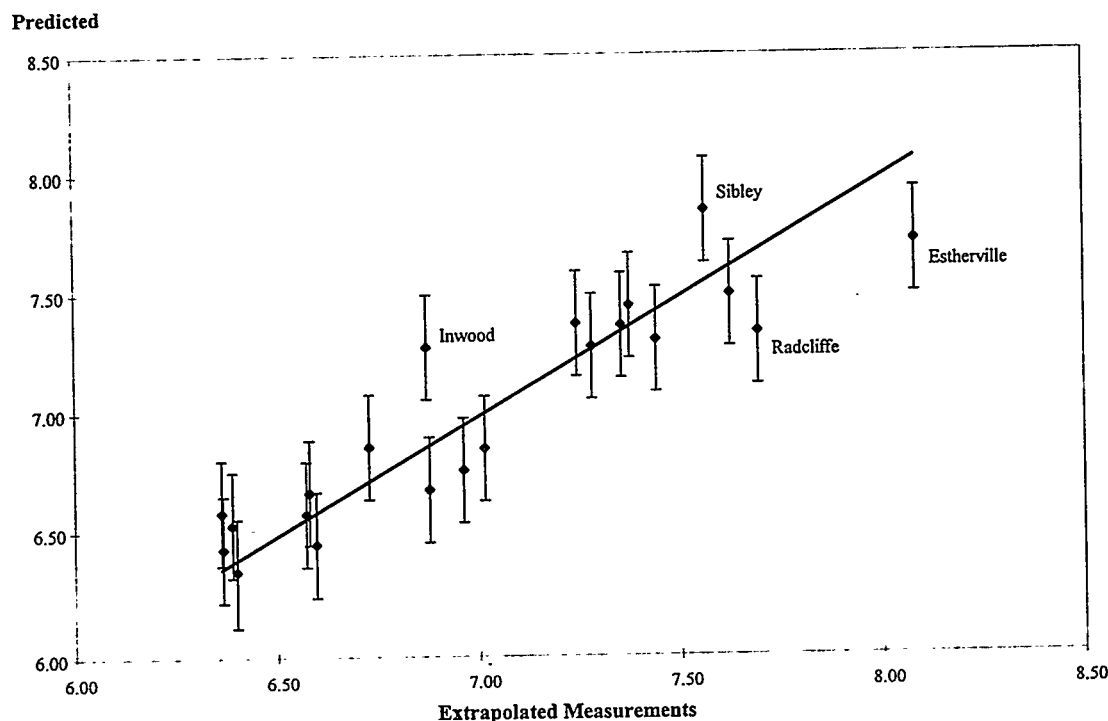


FIGURE 2. Comparison of predicted and measured wind speeds (m/s)

airport stations. The analysis indicates—within the resolution and accuracy of the geographic data—that the strongest determinants of mean wind speed in Iowa are elevation and local terrain roughness, with a secondary influence of terrain exposure. Further research is needed to identify other factors that may affect wind speeds, such as ridge orientation and slope. Nevertheless, the reliability of the model appears to be quite high based on a standard error of 3 percent in the regression fit to the annual wind speed data.

The analysis confirms the general distribution and magnitude of Iowa wind resources depicted in the national wind atlas but with much greater topographical detail. However, caution must be exercised in using these results for predicting the output of wind turbines at a particular location. Local conditions not captured in the model may substantially affect observed wind speeds. Obstructions such as trees and buildings will reduce wind speeds, for example; more rarely, certain land forms may substantially raise wind speeds. Furthermore, the regression model may not be valid in circumstances that fall outside the range of conditions experienced at the 8 NCDC sites and 13 IWEI sites. In particular, we suspect that wind speeds in the hilly areas of northeastern Iowa are not really as low as indicated on the maps.

These maps and their underlying assumptions will be updated with additional monthly data from the 13 existing IWEI sites and 6 new IWEI sites, as well as from the 8 NCDC sites, using USGS topographical maps on a 100 meter grid in the fall of 1997.

WIND POWER IN ERITREA, AFRICA: A PRELIMINARY RESOURCE ASSESSMENT

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ABSTRACT

Our preliminary assessment of Eritrean wind energy potential identified two promising regions: (1) the southeastern Red Sea coast and (2) the mountain passes that channel winds between the coastal lowlands and the interior highlands. The coastal site, near the port city of Aseb, has an exceptionally good resource, with estimated average annual wind speeds at 10-m height above 9 m/s at the airport and 7 m/s in the port. Furthermore, the southern 200 km of coastline has offshore $WS_{aa} > 6$ m/s. This area has strong potential for development, having a local 20 MW grid and unmet demand for the fishing industry and development. Although the highland sites contain only marginal wind resources (~ 5 m/s), they warrant further investigation because of their proximity to the capital city, Asmera, which has the largest unmet demand and a larger power grid (40 MW with an additional 80 MW planned) to absorb an intermittent source without storage.

BACKGROUND

Eritrea won its independence from Ethiopia in 1991 and was validated as a nation by a UN-supervised referendum in 1993. After 30 years of civil war, famine, and poverty, Eritrea's resources are seriously depleted. The country suffers a critical energy shortage that severely limits its economic productivity. Over 80% of the population has no electricity. New supply is critical for both industrial development and to meet basic human needs.

Eritrea's current patterns of energy use are unsustainable. They are rapidly undermining an already precarious national ecological status, and they are in direct contradiction to the nation's goals of pursuing a development path that promotes environmental protection and rehabilitation, while maximizing fiscal and political independence and security. Its current source of electric supply—imported diesel, with a generation cost of about 6 c/kWh—meets none of these requirements. Even more problematic is the fact that 80% of Eritrea's primary energy comes from low-grade biomass produced from virtually denuded lands—a triply precarious path as biomass supplies dwindle, soils erode, and nutrients are systematically removed. With energy demand growing at over 10% per year, unless new, less damaging supply can be rapidly secured, the country faces a grim prospect of productive capacity plummeting, while population skyrockets.

It was thus with admirable understanding and foresight that this young nation, committed itself at the outset to pursuing the potential of indigenous wind and solar energy resources (Government of Eritrea 1995). This wind energy resource assessment proceeds directly from that mandate.

METEOROLOGY AND GEOGRAPHY

The climate of the region is described in detail in the U.S. Navy Regional Climatic Study of the Red Sea and Adjacent Waters (NOCD 1993). The regional wind patterns are dominated by two distinct monsoon seasons separated by two short transition seasons lasting about 30 - 45 days. The dominant winds occur during the dry winter monsoon (November - March), which is produced by the combined effect of the sustained cold high pressure region over the Siberian land mass, complemented by a sustained hot low pressure region centered over southern Sudan, Uganda, and Eastern Zaire (Figure 1a). Winds are swept by Coriolis effect along the pressure contour up the southern Red Sea coast from the southeast, and are enhanced by channeling between the paired mountain ranges on the Arabian Peninsula to the north and the Horn of Africa to the south, which were formed as part of the East African Rift System. The influence of the monsoon is felt up to between 16 and 19 °N latitude, where the winds moving up the coast are met by year-round sustained northwesterlies.

In summertime, the wind direction is reversed in the southern Red Sea, because of an approximate reversal of the high and low pressure zones over the Eurasian and African continents (Figure 1b). This results in consistent summertime northwesterlies down the entire Red Sea, with only modest wind speeds along the Eritrean coast.

The wintertime meeting of the two oppositely moving air streams creates a convergence zone in the Red Sea off the Eritrean coast north of Mitsiwa'e (Figure 2). The convergence zone forms at about 19 °N in December and moves slowly south to about 16 °N by March. The convergence forces air away from the coast, up over the highlands, driven thermally toward the low pressure zone lying just west of the highlands in southern Sudan.

Promising Wind Regions

These features produce two distinct regions that appear to possess Eritrea's most promising wind sites:

(1) The high winds drawn in from the Gulf of Aden are compressed through the narrows of the Arabian and African ranges near the Eritrean port city of Aseb, thus maintaining their power, before falling off at the convergence zone. This, along with several other features make the Aseb region look very promising for wind power development. Most important among these are the facts that: Aseb possesses a local 20 MW electricity grid managed by the Eritrea national utility, which is collaborating with the Eritrean Department of Energy on implementing renewable energy projects; and the local fishing industry has a large unmet electricity demand for refrigeration and ice-making.

(2) The next most promising locations are the mountain passes in the northern highlands that channel and thereby enhance winds drawn out of the convergence zone toward the Sudanese low. Although the winds in these passes appear not to be as strong as the southern coastal winds (see

analysis), the region has the advantage of being near the larger interconnected 40 MW grid that serves the capital city of Asmera. (The Aseb and Asmara grids are the only two substantial distribution systems in the country.) The capital region that has the greatest unmet demand for electricity— both to supply a larger, denser population and to meet development goals. It also has the largest capacity to absorb intermittent power. This capacity will be further enlarged when the currently contracted 80 MW diesel plant is added to the grid.

DATA, ANALYSIS, AND RESULTS

There are relatively few monitoring stations in Eritrea. The National Climatic Data Center (NCDC) in Raleigh, North Carolina archives for only 6 Eritrean stations (Table 1), and most of the datasets are intermittent. In addition, the Eritrean Department of Water Resources has several-year-long datasets for Shambiko, Filfil, Sh'eb, Omhajer, and Tsorena with 15-minute time resolution. The later are non-standard meteorological stations with measurements taken at 3-m height. None of the stations were erected for wind prospecting purposes, thus none were necessarily sited based on an expectation of locally high winds.

Given the very complex topography of the country, the very sparse data, and the regional nature of the winds, we decided early on that a comprehensive assessment with full-country coverage was not possible without a very substantial data collection effort, which is not warranted at this time. Therefore, we chose to first examine those regions appearing to be promising based on the meteorological, institutional, and demographic arguments given above.

TABLE 1. ERITREAN METEOROLOGICAL DATA ARCHIVED BY NCDC.

Stations*	Latitude	Longitude	Elevation (m)	Topographic Region
Aseb	13 04 N	42 43 E	14	coast
Mitsiwa'e	15 37 N	39 27 E	10	coast
Teseney	15 07 N	36 41 E	615	inland massive
Akurdet	15 33 N	37 53 E	626	inland massive
Asmera	15 17 N	38 55 E	2356	inland massive
Nakfa	16 40 N	38 20 E	1676	inland massive

* Note: English spellings of Eritrean place names vary widely. We use here the spellings used on English language maps distributed by the Eritrean government.

Analysis of the Red Sea Coastal Resource

We obtained all hourly-averaged weather data available from NCDC for Aseb between 1977 and 1991. Other years had insufficient data to warrant their purchase. Limitations of the acquired data include data lapses, especially in 1981- 1982, and 1991. The wind speed data contained an abrupt discontinuity in late 1986—the earlier years having average wind speeds approximately 2 m/s higher than the later years. Upon a visit to Aseb, we learned that the earlier years corresponded to measurements at the airport (henceforth referred to as the Airport site), while later years corresponded to measurements in Aseb by the water front

(henceforth referred to as the Town site). We also learned that the data contain both anemometer and human observer-based measurements.

Unfortunately, the high-wind Airport site was systematically missing data for the late evening and early morning hours. Fortunately, the Town dataset was more complete. Since the observed diurnal and seasonal patterns of the two different datasets were very similar for the times they had in common, we were able to use correlation analysis to estimate representative values for the missing times. The "corrected" data were then used to determine the average annual wind speed. A complete description of the analysis, the Weibul parameters, and capacity factors will be included in a future publication.

We also used wind speed data available for the Red Sea itself. We did this both as a cross-check on the "reasonableness" of our Aseb estimates and to determine how far up the coast the rich wind resource extended.

Although many datasets are available for the Red Sea, we settled on using the ship and buoy data compiled in the Comprehensive Ocean-Atmosphere Data Set (COADs), available from NCDC. The COADs dataset is a digital compilation of the raw data that were used in the NOCD (1993) analysis. This dataset was selected for several reasons: the data are based on direct observations made at sea level; data were available for many years (1854 - 1991), although we only used data from 1940 onward because of the poor spatial resolution of the early data; and the raw data were available, as opposed to model-smoothed estimates, which can give very poor results at the desired scale of resolution. We judged satellite scatterometry data, such as the ERS-1 AMI data available from NASA's Jet Propulsion Laboratory, to be unsuitable because of it is known to give poor results near land surfaces.

The COADs data also have certain limitations. They are not typically based on direct measurements of wind speed. Rather, prior to 1963, many of the data were based on visual observations of sea surface roughness, usually recorded using the Beaufort scale. According to NOCD (1993), "such estimates have proven to be quite reliable and can be used with a high degree of confidence". Unfortunately, the uncertainties are not quantified for the data set. We assume an uncertainty level no greater than 1 m/s. Fortunately the poor characterization of uncertainty is compensated by a lack of any source of obvious systematic error, and a relatively long data set with reasonably good spatial coverage.

Our analysis that the WS_{aa} at the high-wind Airport site is above 9 m/s, while during the high wind season the average speed is approximately 11 m/s. The COADS data reveal annual mean Red Sea wind speeds between 6 and 8 m/s off the lower 200-km of coastline, from the village of Saroyta to the Djibouti border. During winter monsoon, wind speeds for the same region average between 8 and 10 m/s (Figure 3).

Analysis of Winds in the Highland Passes

We determined that none of the meteorological station data from the NCDC and the Eritrean government would be representative of good sites in the mountain passes. Therefore, to obtain a preliminary indication of their promise, one of the authors, with the support of the Eritrean Department of Energy, undertook a series of occasional spot-measurements in various passes in the vicinity of the capital. Efforts focused on sites with day-time wind speeds greater than 10 m/s during the high-wind season. Based on these observations and our understanding of the meteorology and topography of the region, we believe that a number of such sites may exist along the ridge-line extending from the Sudanese border in the north to the Ethiopian border in

the south, although they may be enhanced by the convergence in the north. This is the boundary where warm air from the west interacts with the cooler Red Sea basin air.

The spot measurements indicate that winds in these sites can regularly reach 9 to 12 m/s at 5-m height during the high wind season and perhaps even in the transition periods both before and after the winter monsoon. Regular spot measurements at sites located approximately 40 km north and south of Asmera both indicate mean daytime winds of 8 – 10 m/s (approximately twice the velocity in Asmera) during the high-wind season at 5 m elevation. Unfortunately, the winds appear to drop dramatically and predictably at night to less than 1/4 of the daytime peak velocity (also observed in the Asmera).

During the low-wind season, we expect that the winds in the passes will not be much higher than those in Asmera, because enhancement due to inversion layer dynamics should be absent (VanBuskirk *et al.*, 1997). Thus, based on the locally available Asmera data, we presume the low season wind speeds will be approximately 1/2 those of the high-wind season. Using these assumptions, and assuming a 25% enhancement of wind speed at 10-m height, we estimate average annual wind speed in the passes of about 5 m/s (Table 2).

TABLE 2. ASSUMPTIONS USED TO ESTIMATE WIND RESOURCES IN THE PASSES.

Period	Wind speed at 5-m height (m/s)
high-wind season, days	9.0
high-wind season, nights	2.3
low-wind season, days	4.5
low-wind season, nights	1.1
Average wind speed at 5-m height	4.2
Average wind speed at 10-m height*	5.3

* Assumes 25% enhancement over 5-m.

DISCUSSION AND CONCLUSIONS

The results of the analysis for the southern coast indicate a world class wind resource in the Aseb region. The average annual wind speed for the Town site (> 7 m/s) is consistent with the Red Sea wind data off that area of the coast (between 6 - 8 meters per second). The results from the Airport site indicate that careful selection of sites could yield extremely productive, low cost wind power from the region. Because of the cubic dependence of wind power on speed, the 9 m/s site would yield more than a factor of two increase in power over the 7 m/s site. The likelihood of topographic enhancement of winds by coastal hills, and the predictable and regular nature of the monsoon winds, are further reasons for optimism about the resource. In addition, promising wind speeds along the entire southern 200-km of coastline suggest an enormous potential capacity, much more in fact than Eritrea and its neighbors could use for decades to come.

At either 7 or 9 m/s, windpower at Aseb should be low cost compared to the current imported-diesel-based power (at about 6c/kWh). The major barrier to development of this enormous, low-cost wind resource is its seasonal intermittence. Without storage, the intermittent wind capacity would very soon overwhelm the ability of the utility to manage output by balancing the load with the costlier but controllable diesel output. Grubb and Meyer (1993) indicate that

"wind energy should be able to contribute from 25 to 45 percent of the total electricity before operational losses become prohibitive, even in the absence of storage." The relatively low cost of wind power at Aseb might suggest the possibility of penetration at the higher end of the range, but poorer utility performance (in terms of overall power losses and maintenance problems) might well push it toward the lower end or below.

A possible means of circumventing this problem would be to engage in regional power development with Ethiopia (Van Buskirk *et al.* 1997). If Ethiopia were to develop its hydropower resource on the upper Blue Nile Basin, and to swap power with Aseb, the two countries together could produce a much more level supply because the two resources are almost exactly out-of-phase—one generated primarily from the wet-season summer monsoon, the other from the dry-season winter monsoon.

The highland pass sites, although they appear to have marginal winds at about 5 m/s, are worthy of further investigation because of their proximity to the capital. Proximity to the capital has two fold importance: (1) Asmera, with its ideal climate, has the greatest demand from both population and development, and (2) Asmera's electricity grid is not connected to the Aseb region, which is more than 700 km away. A possible intermediate option to supply Asmera would be to locate a wind power plant as far north as possible on the coast (that is, as close to Mitsiwa'e as possible), while still maintaining good output at low cost, and then run a transmission line to the port city of Mitsiwa'e, which already connects to Asmera. Judging the feasibility of such a project will depend on more detailed knowledge of the various resources and the transmission costs. The scale of the regional power share discussed above could be large enough to encompass supply to Asmera.

Based partly on the results of work described herein, the Eritrean Department of Energy is now initiating several wind monitoring efforts in the highland passes and in the Aseb region. This monitoring will allow a more accurate and precise assessment of the resource, its cost, and its potential. The Eritrean government is now pursuing the possibility of a utility scale wind pilot project in Aseb. Funding for continued wind power assessment and development has been awarded through the Global Environment Facility, a joint program between the United Nations Development Program, United Nations Environment Program and the World Bank.

We conclude that the potential for wind energy development in Eritrea is very high. The country has an exceptionally rich wind resource. Wind power is very likely to cost much less than its alternative—imported diesel power. The government has demonstrated its commitment to renewable energy, which will reduce the outflow of currency, increase spending efficiency in the energy sector, reduce environmental costs, diversify supply, and protect against unpredictable fuel price hikes. The international development community has also recognized the potential of windpower to provide Eritrea with power that has low economic and social costs. Indeed, with anticipated international agreements for binding carbon emissions reductions looming at the end of 1997, Eritrea's wind energy development might well become a promising option for foreign countries seeking to achieve reductions targets through emissions trading.

ACKNOWLEDGMENTS

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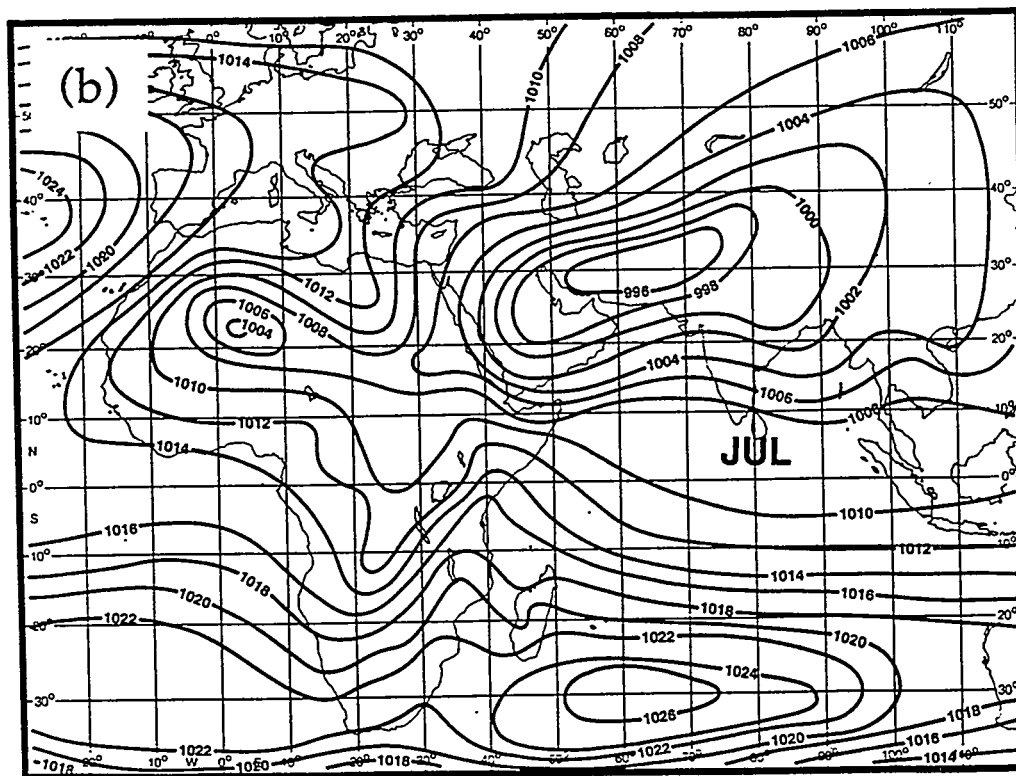
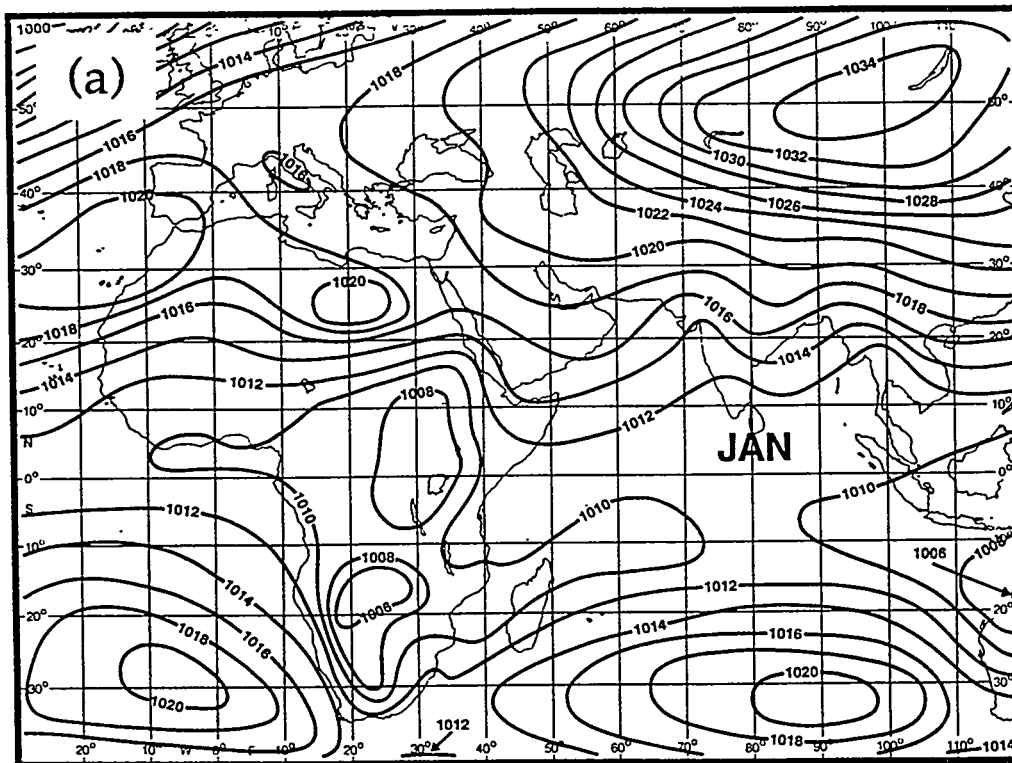


FIGURE 1. SEA-LEVEL PRESSURE. Figure shows regional pressure contours (millibars) that drive the (a) winter and (b) summer monsoons in the southern Red Sea (seasons defined by northern hemisphere climate). Source: NOCD (1993).

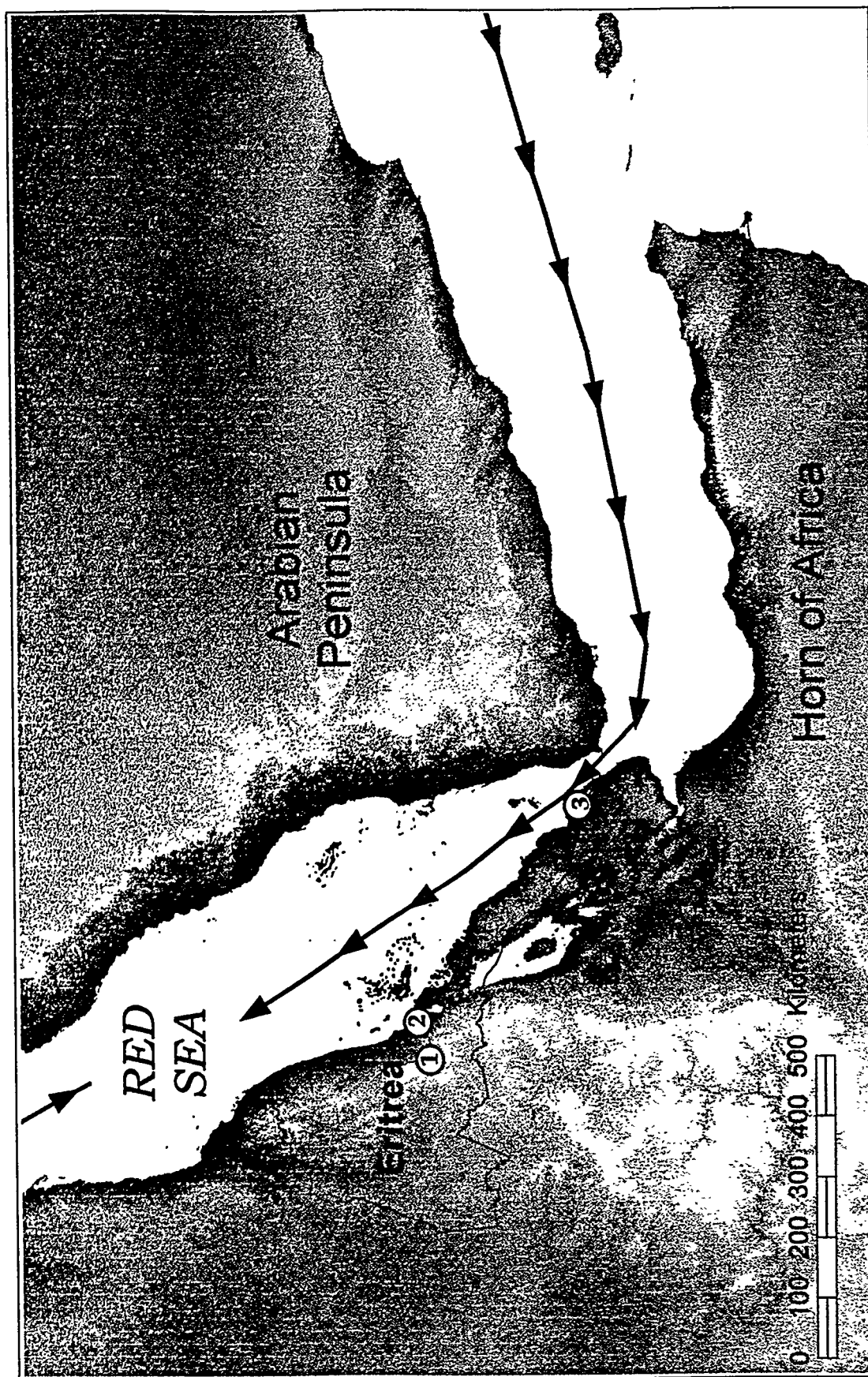


FIGURE 2. WINTER WIND FLOWS OFF THE ERITREAN COAST. Map shows the political boundary of Eritrea, Red Sea wind directions during the high-wind season. City locations are: (1) Asmera, (2) Mitsiwa'e, and (3) Aseb. The shading indicates regional topography; the highland plateau in which Asmera is located has an elevation between about 2000 and 2500 m.

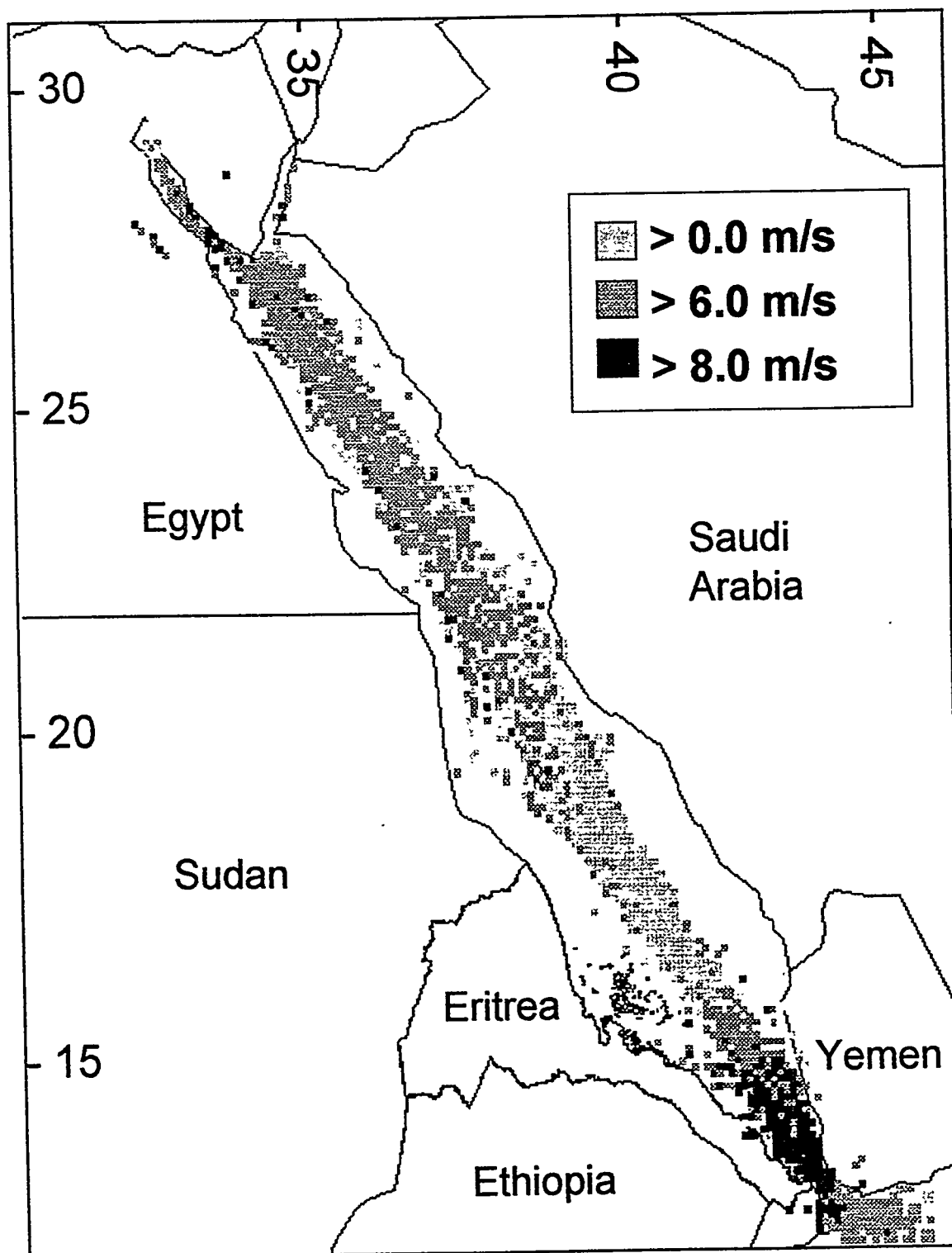


FIGURE 3. OFF-SHORE WIND SPEEDS DURING THE HIGH-WIND SEASON. Wind speeds are averaged from the COADs dataset for the months of October to April (the winter monsoon and adjacent transition seasons).

WIND PLANT CAPACITY CREDIT VARIATIONS: A COMPARISON OF RESULTS USING MULTIYEAR ACTUAL AND SIMULATED WIND-SPEED DATA

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ABSTRACT

Although it is widely recognized that variations in annual wind energy capture can be significant, it is not clear how significant this effect is on accurately calculating the capacity credit of a wind plant. An important question is raised concerning whether one year of wind data is representative of long-term patterns.

This paper calculates the range of capacity credit measures based on 13 years of actual wind-speed data. The results are compared to those obtained with synthetic data sets that are based on one year of data. Although the use of synthetic data sets is a considerable improvement over single-estimate techniques, this paper finds that the actual inter-annual variation in capacity credit is still understated by the synthetic data technique.

INTRODUCTION

Utilities, independent power producers, or other investors in wind power plants must undertake an analysis to determine the likely cost and revenue streams for a project. The revenue from any power plant is typically provided by the sale of energy, capacity, or both. The relative levels of revenue from capacity and energy sales are often specified by contract, and will vary as a function of several variables. Some of these variables include the structure of the company that owns the power plant, the terms of the contract(s), operational practices in the control area, and characteristics of the power plant itself. In other cases, the utility may own the wind plant, but both capacity and energy must still be valued internally. Wind power plants provide an attractive alternative to other power sources because of the free, nonpolluting fuel (the wind itself) that drives the generator. On the other hand, assigning capacity credit for wind plants is complicated by the stochastic nature of the wind availability. With advances in power electronics, it is likely that wind plant operators will be able to exercise greater control over the short-term output of the plant, but this control will still be constrained by the nature of the wind resource. From an operational standpoint a wind plant operator would be able to bid capacity into a pool (or otherwise make commitments on wind power delivery) if he or she possessed an accurate wind forecast for the time period in question. The benefit of accurate wind forecasting is further described in Milligan, Miller, and Chapman (1995).

One significant weakness of most wind plant revenue-stream calculations is that interannual variability in the wind resource is not known. Typically, the developer collects wind data for one year or less. Using hourly wind-speed data, it is then possible to calculate wind power output for each hour. These data can be summarized in a variety of ways and time scales, both in terms of capacity and energy. Estimated future energy production is used as input to the financial model, which provides expected rate-of-return and other financial measures that are used to decide whether or not to build the wind plant. However, the uncertainty that is attached to the estimated wind energy is rarely calculated, and even then, is not likely to be accurate. This implies that the potential wind plant investor is exposed to the risk of basing an investment decision on an unusual wind-year. In order to overcome this difficulty, an analysis of nearby long-term wind data from airports or other meteorological sites can be pursued. This may be the best way to proceed given a lack of measured wind data at the site. The risk from limited data cuts both ways. First, the measured data could be

from a year with unusually low wind, so a good long-term wind site may not be developed. Alternatively, if the measured year has an unusually high wind speed, then the realized revenue stream will fall short of the projected stream.

In this paper a 13-year data set is used to calculate the range of energy and capacity-credit values from the actual data. Representative years are selected on which a Markov wind-speed simulator tool is applied. The wind-speed simulator generates multiple wind-speed series based on the time-scale properties of the original data, allowing for the analysis of plausible wind-speed variations and their effect on capacity credit and other measures of interest.

CHARACTERISTICS OF THE 13-YEAR DATA SET

The data used for this analysis is from an air-quality monitoring site in North Dakota. Data was collected for a 13-year period beginning in 1980. This particular site would not likely be chosen for a wind plant because of the relatively low annual average wind speed. However, until long-term data such as this does become available at potential wind-plant sites, it is useful to examine the data at hand. To compensate for the low wind speed, the data were scaled so that the average annual wind speed matched that at Minot, ND (Sandusky, et. al., 1983). Figure 1 shows the normalized variation in annual energy production for a fictitious 100 MW wind plant. The highest annual energy production for the 13-year period occurred in 1988. During 1981 and 1983 the wind energy capture was approximately 73% of the 1988 level. Over the 13-year period, the average energy capture is about 85% of the maximum, with a standard deviation of 8.7.

Although there is clearly significant variation from year to year, there is a striking variation that occurs when the data is viewed on a monthly basis. Figure 2 plots the monthly energy for three selected years: 1980, 1986, and 1990. These years were chosen to represent mean plus or minus one standard deviation of the annual wind energy production as shown in Figure 1. The months of March and April show extremely high variation in energy output. The month of December exhibits the most agreement between monthly energy levels.

Figure 3 was constructed by taking the maximum, minimum, and mean energy production from the 13-year data set for each month. For example, the maximum series in the graph represents a composite that consists of the maximum energy taken from all 13 January energy values, the maximum from all February energy values, and so on.

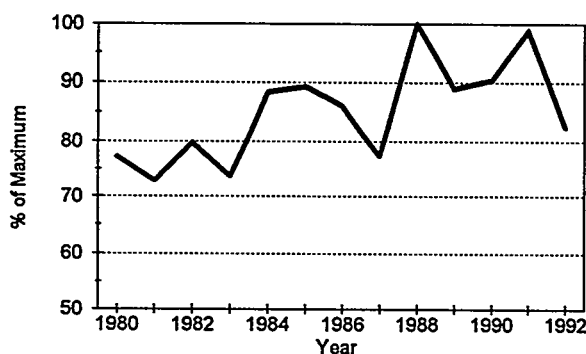


FIGURE 1. ANNUAL ENERGY PRODUCTION

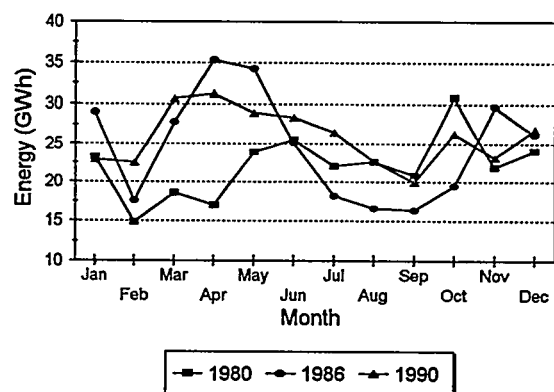


FIGURE 2. VARIATIONS IN MONTHLY ENERGY, SELECTED YEARS

MODELING WITH THE ACTUAL DATA

After calculating the energy production for the 13 years of data, I calculated the capacity credit for each year for a 100 MW wind plant. Elfin is a production-cost/reliability model that has been described in another publication (Milligan, 1996a), and is a product of the Environmental Defense Fund. The model used a load duration curve approximation to calculate costs of energy based on an optimal dispatch strategy that minimizes costs. The model can also be used to calculate capacity credit, which is based on a system reliability index such as loss-of-load expectation (LOLE). Using actual utility load and generator data for Tri-State Generation & Transmission, Association, Incorporated (Milligan & Parsons, 1997), the model was used to calculate the effective load carrying capability (ELCC) for each year of wind data, using a target LOLE of 1 day in 10 years. Figure 4 illustrates the results of these calculations, along with the graph of annual energy production for ease of comparison. As indicated in the diagram, capacity credit and energy production tend to move together, but not always. The reason is that higher energy production may occur in hours of high reliability. In this case, the capacity is not provided when it is most needed to support system reliability and causes a lesser positive impact on capacity credit. This effect was also observed by Milligan and Parsons (1997). As indicated in the figure, there is a relatively high correlation between energy production and capacity credit.

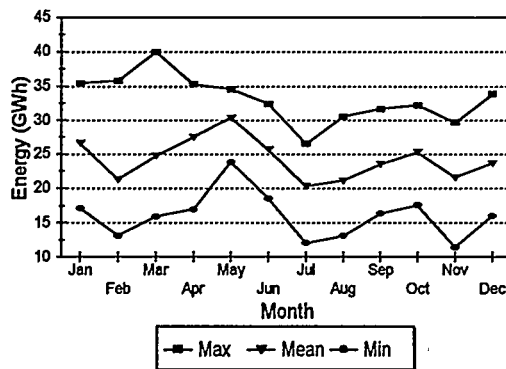


FIGURE 3. MAXIMUM, MINIMUM, AND MEAN MONTHLY ENERGY

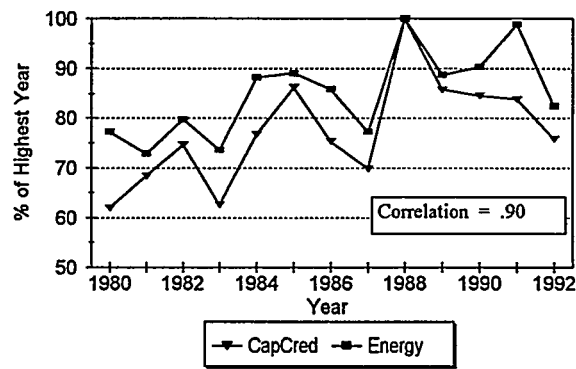


FIGURE 4. CAPACITY CREDIT AND ENERGY FOR 13 YEARS

Table 1 shows the variation in energy and capacity credit, as measured by the coefficient of variation (COV), defined by the ratio of the standard deviation to the mean. The ELCC has a higher variation than energy because relatively small shifts in the timing of wind energy delivery can have a significant impact on system reliability, and thus the capacity credit of the wind plant.

TABLE 1. CAPACITY CREDIT AND ENERGY FROM ACTUAL DATA

Data	Average	Standard Deviation	Maximum	Minimum	Coefficient of Variation (%)
Energy (GWh)	291.7	30.0	343.3	250.0	10.3
ELCC (MW)	39.1	5.4	50.5	31.3	13.8

MODELING WITH THE SIMULATED DATA

Using the actual wind-speed data from each of the 13 years, I selected 3 years to represent high-wind (1990), low-wind (1980), and mean-wind (1986) cases. The high and low years approximate one standard deviation above and below the mean, respectively. Using these three years, a Markov wind-speed simulation tool was used to generate 100 time-series of wind power for each selected year. This process has been described in Milligan (1996b) and resulted in a total of 300 wind power time-series. Figures 5 and 6 illustrate two of the state-transition matrices calculated from the actual data for July 1980 and July 1981, respectively. The 3 large spikes at the high wind-speeds in Figure 6 illustrates a much higher probability of high-wind events than in 1980. The large variation in state-transition matrices is consistent with that found in the wind-speed and wind-power data illustrated by some of the previous graphs.

State-transition matrices such as those shown in Figures 5 and 6 were used to generate the synthetic wind-speed data for the 300 time-series. Using actual wind-speed data, a state-transition matrix was calculated for each month. The resulting distribution was sampled to create a large number of time-series of wind-speed data. Each of these series consists of one year of hourly wind-speed data which was then used to calculate hourly power output for the hypothetical wind plant. Each of these 300 data series was then processed by the Elfin production-cost model. Elfin was executed repeatedly for various utility load levels to determine the ELCC of each of the 100 wind power time-series for each of the 3 selected years. The discussion separately considers each of the three years, followed by some observations of the combined results.

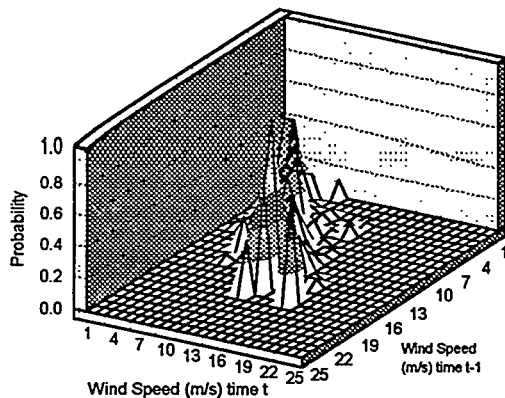


FIGURE 5. STATE TRANSITION MATRIX,
JULY, 1980

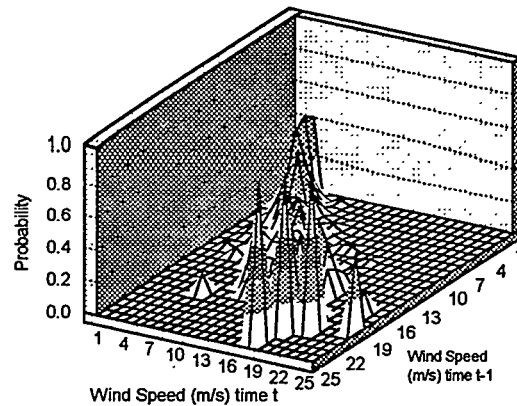


FIGURE 6. STATE TRANSITION MATRIX
JULY, 1981

HIGH-WIND YEAR RESULTS

Figure 7 shows the results for the high-wind year, 1990. The graph shows the ELCC results for each of the 100 cases for the year. The average ELCC for the 100 cases is 42.3 MW, which very closely approximates the ELCC that was calculated from the actual data, 42.7 MW. Using the Markov approach does result in years with varying capacity credits, in this case ranging from a minimum of 30.5 MW to a maximum of 52.5 MW. Both the maximum and minimum are close to those calculated from the actual data, as displayed above in Table 1. Figure 8 shows the convergence of the high-wind simulations. The convergence factor is the ratio of the cumulative standard deviation to the cumulative mean (see Milligan, 1996b). Inspection of the convergence factor indicates that the stability of the results is still in doubt until about 70 Markov iterations

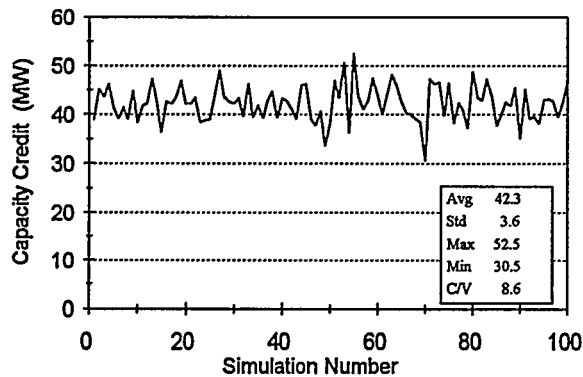


FIGURE 7. ELCC RESULTS FROM HIGH-WIND YEAR, 1990

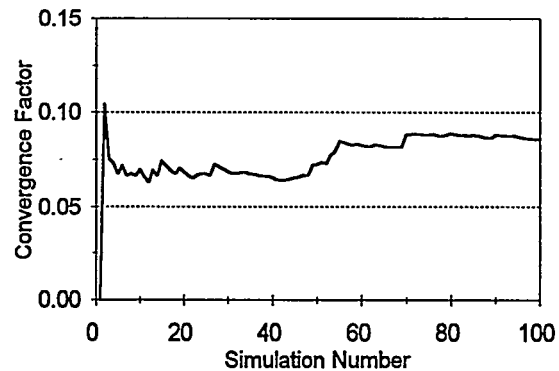


FIGURE 8. CONVERGENCE OF ELCC RESULTS, 1990

have been performed. It would be useful to provide the model with convergence criteria instead of a fixed number of iterations. However, as discussed in Milligan (1996b) this cannot be accomplished with the Elfin model. Billinton, Chen, and Ghajar (1996) find that convergence is achieved after approximately 6,000 iterations using an integrated auto-regressive moving-average (ARIMA) process to model wind speed. Figures 9 and 10 show further results from the 1990 simulations. Figure 9 illustrates the frequency distribution of the ELCC values. The bin sizes correspond to the standard deviation of ELCC, and the middle bin contains all ELCC values within $\frac{1}{2}$ standard deviation either side of the mean. Figure 10 shows the energy obtained by the Markov simulation process for each of the 100 cases. As was the case with the actual data, there is more variation in ELCC than energy. The mean energy value is very close to the actual energy for 1990, as one would expect.

MEAN-WIND YEAR RESULTS

Figure 11 shows the capacity credit results for the mean-wind year. As expected, the average, maximum, and minimum ELCC values are less than those of the high-wind year. The coefficient of variation is somewhat higher than the high-wind case because of a smaller mean and slightly higher standard deviation. Figure 12

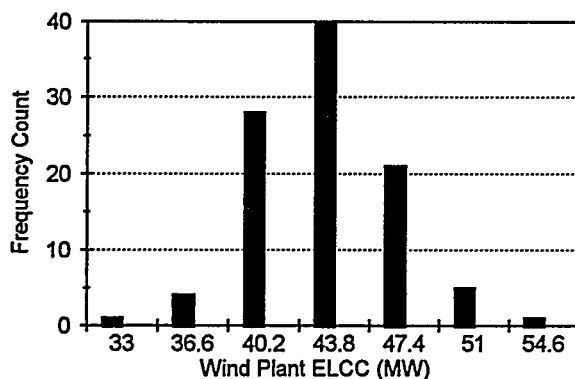


FIGURE 9. ELCC FREQUENCY DISTRIBUTION, 1990 SIMULATIONS

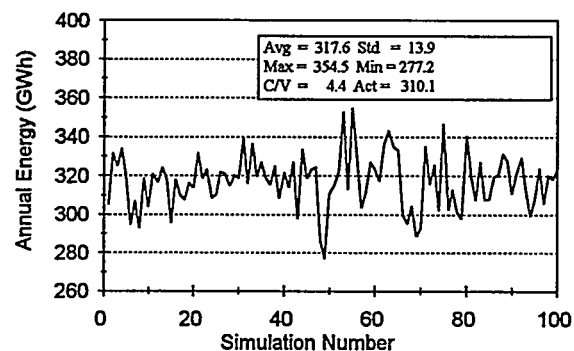


FIGURE 10. ENERGY RESULTS FROM HIGH-WIND YEAR, 1990

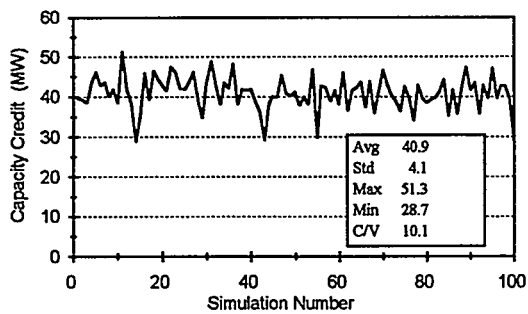


FIGURE 11. ELCC RESULTS FROM MEAN-WIND YEAR, 1986

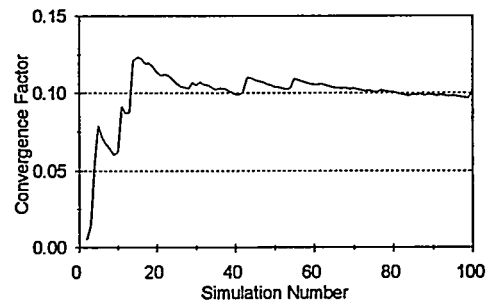


FIGURE 12. CONVERGENCE OF ELCC RESULTS, 1986

shows the convergence factor for 1986. Relative stability appears to be reached after about 70 iterations—about the same point as for the high-wind year.

Figures 13 and 14 show the ELCC distribution and energy results from 1986. With the exception of a few outliers in the left-most bin, the shape of the distribution is nearly symmetrical. The mean, maximum, and minimum energy values are less than those of the high-wind year, as expected.

LOW-WIND YEAR RESULTS

Figures 15-18 show the results from 1980, the low-wind year. The average ELCC value for this year is about 4.5 MW less than the mean case. The results from the low-wind case parallel those of the other cases, with correspondingly lower ELCC and energy values.

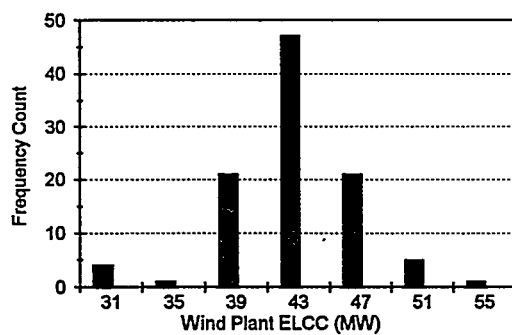


FIGURE 13. ELCC FREQUENCY DISTRIBUTION, 1986 SIMULATIONS

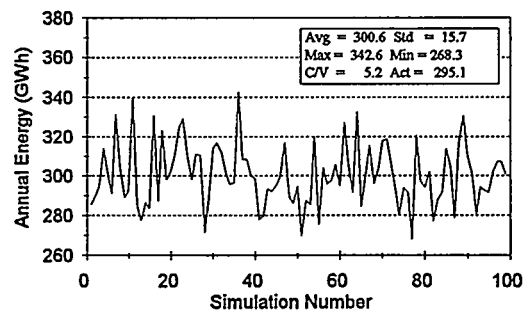


FIGURE 14. ENERGY RESULTS FROM MEAN-WIND YEAR, 1986

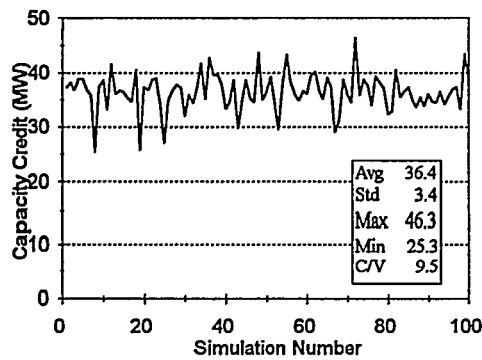


FIGURE 15. ELCC RESULTS FROM LOW-WIND YEAR, 1980

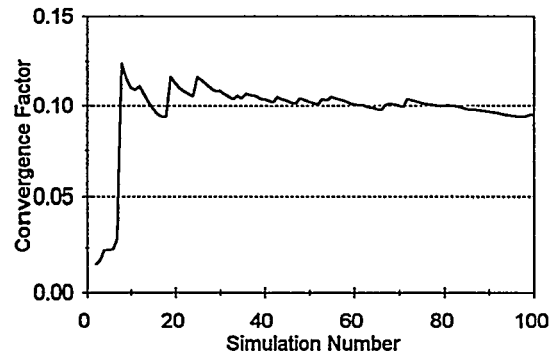


FIGURE 16. CONVERGENCE OF ELCC RESULTS, 1980

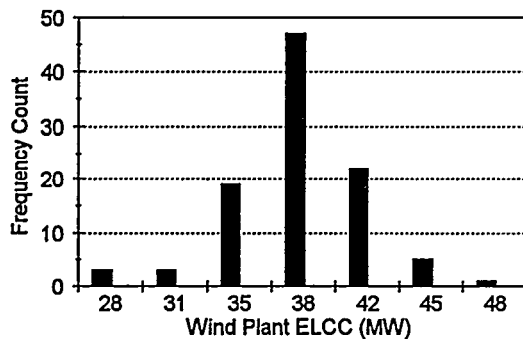


FIGURE 17. ELCC FREQUENCY DISTRIBUTION, 1980 SIMULATIONS

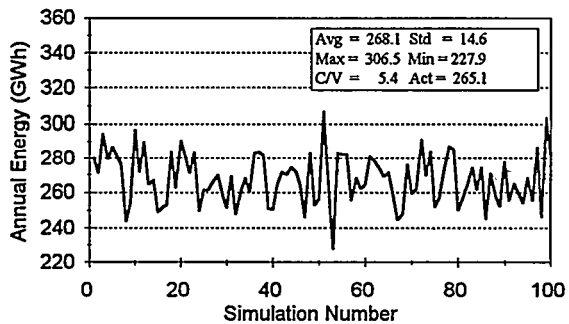


FIGURE 18. ENERGY RESULTS FROM MEAN WIND-YEAR, 1980

COMBINED RESULTS

Tables 2 and 3 gather the results from the various simulations discussed in the previous sections. Table 2 shows the ELCC results for each of the high-, mean-, and low-wind years. The actual data results are included in the first row for convenience. The variation of the simulated ELCC values as measured by the range overestimates the variation in the actual data. Conversely, the coefficient of variation from the simulated data sets underestimates the variation in the actual data set. The simulated energy ranges in Table 3 all significantly understate the variation in the actual data, as do the coefficients of variation.

What are the implications of this work? If data has been collected for a single year that nearly matches a long-term mean year, then the Markov approach does a reasonably good job of predicting the likely range of ELCC values, but underpredicts variations in annual energy. To accurately predict energy variations another method would be required.

If a single year of wind data is collected, the important question is whether that is a typical-, high-, or low-wind year. In some cases data for the measured year can be compared with other long-term data records to establish

TABLE 2. ELCC SIMULATION COMPARISONS

Wind Data	Average	Standard Deviation	Maximum	Minimum	Range	C/V (%)
Actual	39.1	5.4	50.5	31.3	19.2	13.8
High-Wind Year	42.3	3.6	52.5	30.5	22.0	8.6
Mean-Wind Year	40.9	4.1	51.3	28.7	22.6	10.1
Low-Wind Year	36.4	3.4	46.3	25.3	21.0	9.5

TABLE 3. ENERGY SIMULATION COMPARISONS

Wind Data	Average	Standard Deviation	Maximum	Minimum	Range	C/V (%)
Actual	291.7	30.0	343.3	250.0	93.3	10.3
High-Wind Year	317.6	13.9	354.5	277.2	77.3	4.4
Mean-Wind Year	300.6	15.7	342.6	268.3	74.3	5.2
Low-Wind Year	268.1	14.6	306.5	227.9	78.6	5.4

how the measured year compares to a longer period. Once this determination is made, the Markov method could be used to calculate the estimated variations.

Several caveats should also be pointed out. First, these results may not be robust to other wind sites. The North Dakota data used in this report does not have a significant diurnal component, as the wind is primarily caused by synoptic-scale weather events. This data was obtained from an air-quality monitoring site that would not be utilized for a wind power plant. Second, it is likely that a significantly longer data set should be used to establish the wind-speed characteristics of a site. Finally, all capacity credit calculations are sensitive to the correlation between the utility load and wind resource and to the specific utility resource mix during peak and off-peak periods. ELCC is also sensitive to the level of the risk-target chosen by the utility management and whether the LOLE or energy-not-served or other reliability measure is chosen as the appropriate risk measure.

CONCLUSIONS

This paper has presented a method to estimate capacity credit variations of wind power plants, using synthetic data generated with a Markov process. The state-transition matrices are based on actual wind-speed data. Although there is room for improvement, the method does a reasonably good job of providing an estimate of capacity credit, as measured by ELCC. This method is not particularly effective for estimating energy variations, an area that needs further investigation.

ACKNOWLEDGMENTS

This work was supported by the United States Department of Energy under contract DE-AC36-83CH10093. The author gratefully acknowledges the helpful discussions and comments provided by Thomas Brookman of the Orlando Utilities Commission, Alan Miller of Problem Solvers International, and Brian Parsons and Kristin Tromly of the National Renewable Energy Laboratory. Thanks also to Mark Graham of Tri-State Generation and Transmission Association, Incorporated, for providing load and generator data.

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RESULTS FROM AN INVESTIGATION OF THE INTEGRATION OF WIND ENERGY INTO THE EL PASO ELECTRIC GRID SYSTEM

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ABSTRACT

This paper documents some preliminary results from an evaluation of the costs and benefits to be gained from the integration of wind generated electricity into the El Paso Electric grid system. The study focused on the utilization of the considerable known wind potential of the Guadalupe/Delaware Mountains region, but also looked at other energetic wind resources within 15 miles of El Paso Electric's Grid. The original project's goal was to identify the added value of wind in terms of jobs, line support, risk reduction etc., that wind energy could bring to El Paso Electric. Although these goals have not yet been achieved the potential for water savings and reductions in gaseous emissions have been documented. Thus this paper focuses mainly on the water consumption and criteria pollutant emissions that could be avoided by adding wind energy to El Paso Electric's generation mix. Preliminary data from a renewables attitude survey indicates that, from the 338 respondents, there is overwhelming public support for utilizing such renewable sources of electricity. This case study, which should be of direct relevance to the arid southwestern states and beyond, was sponsored by the Environmental Protection Agency (EPA) and conducted in cooperation with El Paso Electric.

INTRODUCTION

El Paso Electric's service territory covers the western extreme of the state of Texas and reaches north into New Mexico. The customer base consists, primarily, of the city of El Paso and its environs, but also includes sales to Juarez, Mexico. The climate is extremely dry, with little annual rainfall. Although the Rio Grande River runs through the area, the major source of water has been from wells drilled into the underlying aquifers. As a consequence of rapid regional growth, these aquifers are being depleted. Increases in the price of water and media campaigns to raise public awareness are integral parts of the El Paso Water Utilities attempts to reduce water consumption.

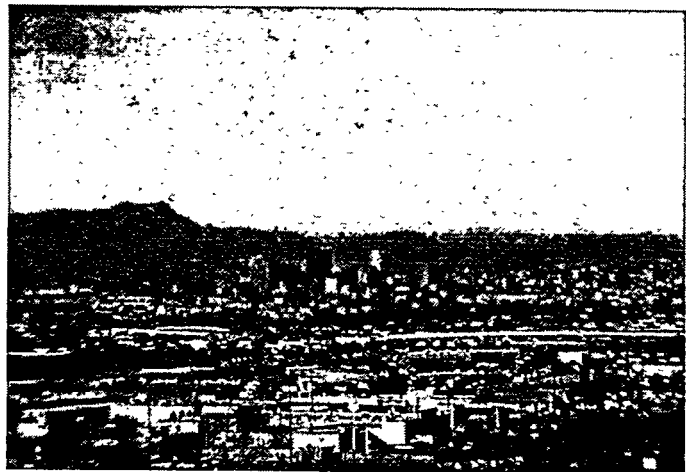


Figure 1 Haze over downtown El Paso

According to the EPA (1), the El Paso/Juarez border region is an air quality non-attainment area that exceeds ambient air quality standards in particulates (PM-10), Carbon Monoxide (CO), and Ozone. The problem is most noticeable from mid October through March when temperature inversions are common and, as shown in Figure 1, a brown haze hangs over the city. Border residents are concerned that these air quality problems have important implications for their health. While the EPA believes that the principal

sources of the criteria pollutants originate from local industry, automobiles and the burning of waste in Mexican' landfills (1), they have yet to quantify the exact sources.

El Paso Electric Company (EPE) has the capability of producing an estimated 800 MW of electrical power, from natural gas fired intermediate and peaking power generating units, within the city of El Paso and owns 104 MW from the Four Corners coal fired power plant and 600 MW from the Palo Verde Nuclear power plant. Thus, although it is not the largest producer of pollution within the El Paso air shed when compared with vehicular traffic and emissions from Mexico, it does contribute to the poor air quality and to greenhouse gases by burning fossil fuels close to the city. Furthermore, it relies on considerable quantities of water for cooling purposes. Not only does this place a demand upon the regionally critical water resource, but the evaporative cooling process leads to a disposal problem for the non-evaporated water (blowdown) which is left with a relatively high concentration of minerals by the cooling process.

A significant wind resource had been previously identified on the fringes of the El Paso Electric Service territory, in the Delaware Mountains, and is in the early stages of being exploited (2). A 35 MW windfarm was recently commissioned and the potential for at least another 700 MW of wind power exists in that area. This resource, which creates no gaseous emissions and does not require water to produce electricity, has the potential to improve the regions air quality and water supply problems by reducing water consumption and displacing fossil fuel generated power that would otherwise be produced within the city of El Paso. Despite the relative proximity of such a significant wind resource, local utility decision makers are reluctant to invest in it, due to the current low cost of gas, concerns about deregulation, and doubts about the value of an intermittent resource, such as wind energy.

It should be made clear that EPE conforms to all Federal, State and local regulations. Furthermore it burns what is generally considered to be the cleanest fossil fuel: natural gas. This paper strives to raise awareness of the potential air, water and public relation benefits that investing in a modest amount of wind energy could bring to the company and the inhabitants of the region.

THE WIND RESOURCE

In order to quantify the extent of the local wind resource a Geographical Information Systems (GIS) study was conducted covering the El Paso Electric service territory, by the Alternative Energy Institute (AEI). Their results point to a considerable wind resource in the region. A number of large areas of interest within 15 miles of the EPE grid lines were identified. These consist of a Class 6 region to the northeast of El Paso and a Class 4 region at the eastern extremity of the EPE grid, near Van Horn, TX. The other significant region, originally mentioned as the focus of this project, was the Guadalupe/Delaware Mountain Class 7 area. Access to the latter would have to be negotiated with Rio Grande Cooperative, which owns the power lines nearest that site. Thus the resource was documented and the potential for line support, through the location of windfarms at the ends of long transmission lines identified. (The ability to feed power almost directly to customers at the end of transmission lines has value since it avoids transmission line losses.)

For a preliminary evaluation of any coincidence between the demand for power and the availability of wind generated electricity, one years worth of wind data was obtained for two potential wind sites. AEI provided hourly averaged wind data collected at Guadalupe Pass and the Hueco Mountains for the year starting 1 September 1995 and ending 31 August 1996. EPE provided hourly electrical demand data for the same period. Figure 2 shows a comparison of normalized daily averages for a hypothetical windfarm with the EPE load. It is clear from this figure, that despite the fact that there are exceptional winds in the

winter and springtime, the summer peak demand corresponds to the period of lowest wind power production. This fact would most likely reduce the value of wind energy in the eyes of EPE, since they are a summer peaking utility. However, the relative abundance of wind energy during the springtime would allow the utility to decrease its dependence on purchased power and to reduce its loss of load probability, during this time of scheduled maintenance for its largest power plants.

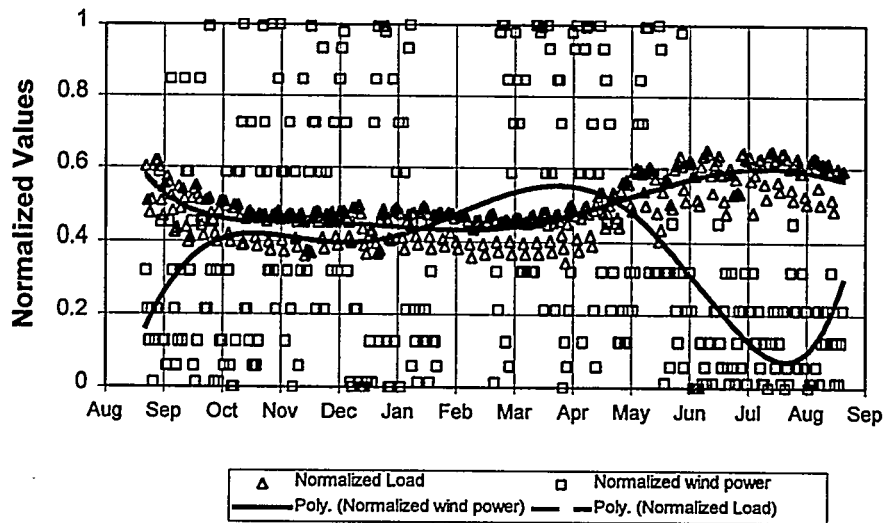


Figure 2. Comparison of Normalized EPE Load and Power Output from a Hypothetical Windfarm (Data for 1 September 1995 to 31 August 1996)

A further analysis was conducted to look at the diurnal wind patterns and to compare these with the electrical load. Figure 3 shows a good match between wind power and load for the spring, but Figure 4 indicates a poor match during the summer. From the annual data, the minimum capacity factor is approximately 7.5%. This should be contrasted with data from the Lower Colorado River Authority (LCRA) that indicated more favorable summer winds than were found in this study (2). Perhaps of more significance regarding air quality non-attainment, an evaluation of the wind speed at Guadalupe Pass versus the concentrations of CO measured in downtown El Paso, for January 1997, was conducted. It showed that there was a greater than 50% probability that reasonable quantities of wind power would be available to displace conventional power production during inversion phenomena. This surprising result, which needs further verification, is thought to be a consequence of the local wind drivers and the approximately 100 mile separation between the Guadalupe Pass wind regime and downtown El Paso.

In summary preliminary indications are that wind provides its highest capacity factors during the part of the year when the utility takes its larger units off line for maintenance and that wind power generated at the extremes of the transmission lines is likely to displace gaseous emissions during inversions. However, the wind does little to alleviate the summer peak load. It should be noted that more data is necessary in order to confirm these trends.

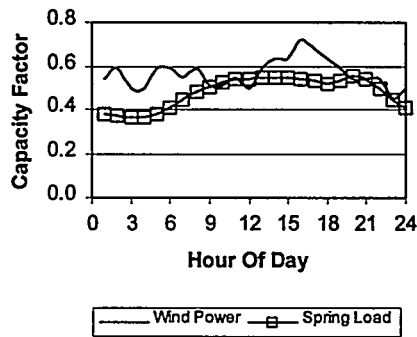


Figure 3. Spring Wind and Load

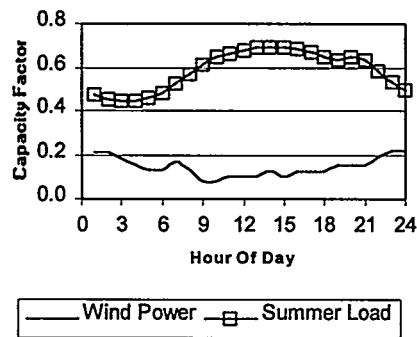


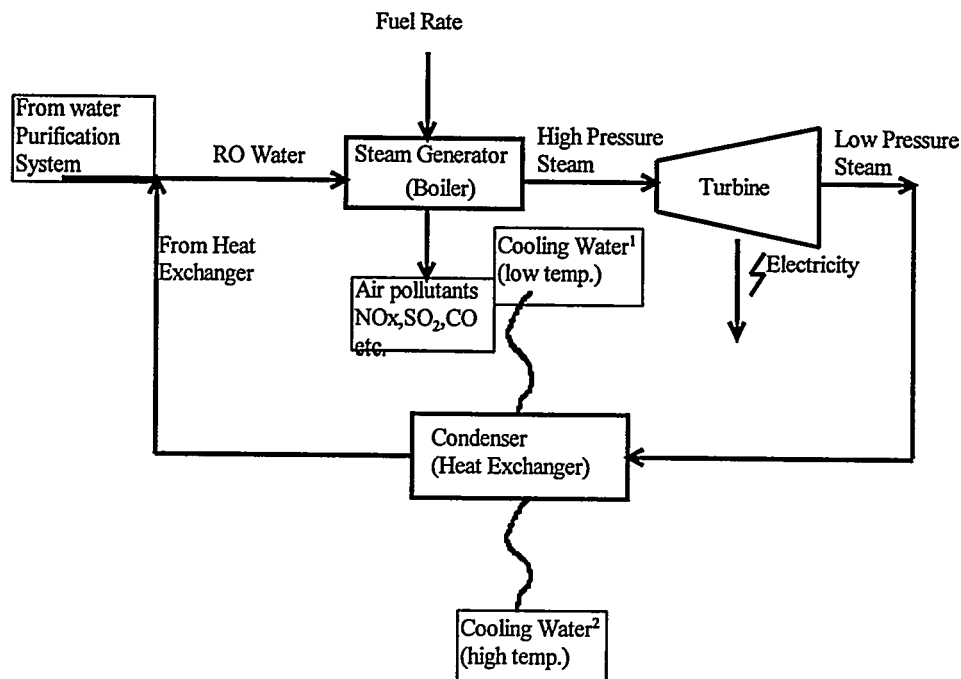
Figure 4. Summer Wind and Load

ENVIRONMENTAL IMPLICATIONS OF DISPLACING CONVENTIONAL POWER WITH WIND ENERGY

El Paso Electric has three power plants within the environs of El Paso: the Rio Grande power station, which has a capacity of 246 MW and utilizes steam electric generators; the Newman power station has a capacity of 482 MW with a mixture of steam electric and gas turbines; and the Copper plant with a capacity of 68 MW which utilizes a single gas turbine unit. The primary source of fuel is natural gas, but the utility maintains reserves of oil, for emergency backup. In our study of water consumption and gaseous emission only the largest two power stations were considered.

Bill Hoffman of the Texas Water Development Board points out, in his paper on the "Relationship Between Water and Energy use in Texas" (3), that while Texas has already developed 75 to 80 percent of all conventional ground and surface water resources, "as much as 25% of the energy Texas produces ends up evaporating water –making clouds!!!" Although the principal El Paso Water Utilities consumption is attributed to residential users, EPE as a consequence of its dependence on fossil fuels also consumes large volumes of water. However, on a percentage basis, their water consumption is only about 5.6 % (if tertiary water is included) of the total of El Paso Water Utilities annual consumption. Nevertheless this equals many hundreds of millions of gallons of water being converted to steam in the middle of a desert. A small fraction of this water coming from the Hueco Bolson that, according El Paso Water "will be depleted to the level of unrecoverable storage around the year 2025" if present trends of water usage continue (4). In order to understand what effect wind energy or some other renewable source of energy could have in reducing regional water consumption it was necessary to understand how water was used by EPE in the production of conventional electricity.

The water consumption at EPE is classified into three types: boiler make-up water, cooling water, and service water. Boiler make-up water contains very low concentrations of dissolved solids and is created by a Reverse Osmosis (RO)/Deionization (DI) process. This water is used to generate high pressure steam necessary to turn the turbine that drives a generator. Cooling water is used in condensing the steam, which is then returned back to liquid boiler water. Most of the service water is used to cool ancillary devices. Figure 5 depicts a typical steam cycle.



1. The cooling water is recirculated 5 times both at the Rio Grande and Newman plant.
2. At Rio Grande power station blowdown is discharged into the river by NPDES permit. At Newman, blowdown discharge is sent to an evaporation pond and EPE is allowed to irrigate El Paso Water Utilities property located around Newman Power plant

Figure 5. Schematic diagram of a steam electric power plant

At the Rio Grande plant, the cooling water comes from EPE's seven privately owned wells while RO feed water and service water are city water purchased from El Paso Water Utilities. At Newman, the cooling water is tertiary water, or treated effluent water, which is purchased from El Paso Water Utilities at a special rate. The service water and RO feed water for Newman are all self-supplied water from wells drawing on the endangered Hueco Bolson (aquifer). Table 1 gives the annual water consumption from the Rio Grande Power Plant, the average rate being 0.849 gallons/kWh. While the 1996 data, shown in Table 2, indicates that Newman Power Plant uses 0.61 gallons/kWh.

Table 1 Annual Water Consumption at Rio Grande Power Plant: 1992-96

Year	Gross Power (MWh)	Well Water (gal)	Purchased City water (gal)	Total (gal)	Gallons/kWh
1992	591,363	550,981,456	27,485,942	578,467,398	0.978
1993	1,015,026	772,527,551	30,889,797	803,417,348	0.791
1994	1,042,562	764,402,637	32,709,927	797,112,564	0.765
1995	919,584	794,926,548	36,728,715	831,655,263	0.904
1996	880,018	682,354,803	28,552,656	709,897,600	0.807

Table 2 Annual Water Consumption at Newman Power Plant in 1996

Year	Gross Power (MWh)	Well Water (gal)	Purchased Treated Effluent (gal)	Total (gal)	Gallons/kWh
1996	1,951,130	348,995,000	841,092,624	1,190,087,624	0.61

In order to attribute a cost to the use of water for power production one must not only consider the value of the water but also the cost of chemical treatments, pumping, labor and the reverse osmosis process. Table 3 documents the cost breakdown for the Rio Grande Power Plant while Table 4 does the same for the Newman Power Plant. From these tables it can be seen that there are some broad differences in cost, with the cost of the reverse osmosis process being the most expensive per gallon. In Table 3 the cost of the self-supplied cooling water is much lower than the cost of purchasing water from the city, for use as service water. In Table 4 the cost of the cooling water, which is treated effluent water purchased from the city, is relatively modest, compared to Rio Grande service water or RO water. However by 2001 this figure is due to rise to 80% of the commercial rate at which water is sold to the general public (at 1997 rates, for tertiary water, that would mean that the utility would have to pay over twice the 29 cents it paid in 1996.) Thus the cost of water is due to rise dramatically.

Table 3 Water Usage Information for Rio Grade 1996

Type of Water	Percentage of total	1,000gal/MWh	Water Quality (mmho)	Cost (per 1,000 gal)
Cooling water	96	0.7754	1,800	\$0.02
Service water	2.1	0.01546	1,200	\$1.04
RO water	1.9	0.01699	10	\$6.85

Note: cost details obtained from EPE

Table 4 Water Usage Information for Newman 1996

Type of Water	Percentage of total	1,000gal/MWh	Water Quality (mmho)	Cost (per 1,000 gal)
Cooling water	70.7	0.4311	N/A	\$0.291
Service water	18.6	0.1137	1,200	\$0.264
RO water	10.7	0.0652	10	\$2.10

Note: cost details obtained from EPE

Calculating the value of water saved through investment in a 50 MW windfarm:

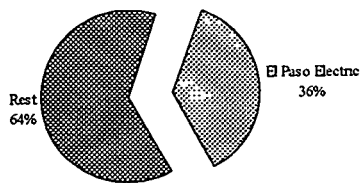
If it is assumed that a 50 MW windfarm is sited in a good class 6/7 wind site, such as the Guadalupe/Delaware Mountains, one can conservatively expect an annual power output in excess of 150,000 MWh (this figure being the average of power predicted by the LCRA (2) and values calculated using an extract from the 1993 EPRI Technical Assessment Guide, provided by EPE). If this amount of energy displaced an equivalent amount of fossil fuel generated power that would have been produced at the Rio Grande power plant then, for 1996, a total of 121,213,500 gallons (0.36% of total El Paso Water Utilities annual sales) of water would have been saved. A cost savings of $(0.02 * 116,310) + (1.04 * 2,319) + (6.85 * 2,584.5) = \$22,195$, would also be realized. This modest figure increases to \$140,831 if the missed opportunity of selling the well water to the public is included.

For Newman power plant a smaller water saving of 91,500,000 gallons (0.29% of total El Paso Water Utilities annual sales) could be realized with a slightly higher cost savings of $(0.291 * 64,665) + (0.264 * 17,055) + (2.10 * 9,780) = \$43,858$. This value would increase to \$66,426 if the full cost of tertiary water were factored into the calculation. (It should be noted that the full cost of tertiary is to be charged in 2001, when a special dispensation expires).

In summary it appears that more water could be saved if energy is displaced from the Rio Grande Power plant. While more money could be saved, at 1996 rates, if water were displaced from Newman Power plant.

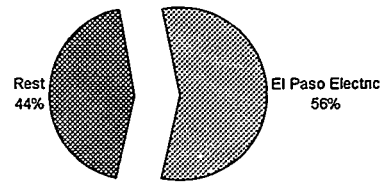
Calculating the amount of gaseous emissions avoided by a 50 MW windfarm:

The gaseous emissions from the Rio Grande and Newman power stations are monitored by EPE and reported to the regulatory agencies in Texas and New Mexico. From the Texas Natural Resources Conservation Commission (TNRCC) data, plotted in Figures 6 and 7, one can see that EPE is a significant contributor to the industrial emissions in El Paso County. Of the industries in El Paso County, EPE is the largest single emitter of the criteria pollutant CO, and the largest single emitter of NO_x (a precursor to Ozone). However, it is estimated that 60 % of all emissions to the air are from mobile sources and that if Ciudad Juarez, Mexico is considered then the percentage contribution, by EPE, is relatively small. Mark Rodriguez, Environmental Scientist with EPE, stated that "all of the (electricity) generating stations have been identified by the EPA and TNRCC as operating outside the carbon monoxide (CO) non-attainment area and the Texas' generating units (Newman and Copper) have obtained exemption for the control of nitrous oxide (NO_x) compounds based on the 1990 Clean Air Act Amendments section 182(f)." That said, it is the author's contention that all emitters of gaseous pollutants have a responsibility to strive for improvement. If change is not voluntary, then there is likely to come a time when it becomes mandatory and those that are the largest emitters will carry the greatest risk of the costs associated with compliance.



Source: TNRCC, Air Quality Planning Division, Emissions Inventory Section

Figure 6. Industrial Emissions of NOX for El Paso County in 1994



Source: TNRCC, Air Quality Planning Division, Emissions Inventory Section

Figure 7. Industrial Emissions of CO for El Paso County in 1994

If a 50 MW windfarm was built that displaced 150,000 MWh of fossil fuel generated electricity then the emissions of NO_x, SO₂, CO and CO₂ will be reduced as listed in Table 5. At this point the pollution credits for avoiding these emissions have not been evaluated.

Table 5 Pollutants Reduced by a 50 MW Windfarm

Power Plant	NO _x (ton)	SO ₂ (ton)	CO ₂ (ton)	CO (ton)
Rio Grande	744.8	0.416	431,400	8,048
Newman	945.8	0.416	431,400	1,034

1. Data provided by EPE
2. 1000kg = 1 ton

EVALUATION OF THE NON-TRADITIONAL VALUE OF WIND ENERGY

While windfarms are being built for 5 cents/kWh or less (5) EPE personnel, like the authors of the 1993 "Standard Handbook for Electrical Engineers" (6), appear to view wind energy only as a fuel saver and attribute to it a value of around 1.5 cents/kWh. Even using these numbers, if a 50 MW windfarm were to be built by EPE and the additional 3.5 cents/kWh (0.035 x 150,000,000) spread evenly across EPE's estimated 6 x 10⁹ kWh of annual sales, then an average household (with a monthly consumption of 500 kWh) would only pay an extra 44 cents a month. The figure would be much less if the non-traditional values of wind energy were included.

Although not complete at the time of writing "standard capital budgeting practice" is to be applied to the issue of independently determining the cost of energy. This approach is being used in order to avoid any institutional biases and assumptions. Dr. Traichal intends to identify any embedded options (non-traditional values) and hopes to provide a valuation, using an option valuation technique such as the Black-Scholes formula. For example the variance in the price of natural gas will be investigated. To avoid arguments about assumptions the calculations are to be made based upon a range of scenarios. It is in this unfinished part of the project that a broad range of economic attributes deriving from the use of wind energy will be elaborated upon. The objective being to determine whether non-traditional values can be identified that will help to increase EPE's perceived value of wind energy.

PUBLIC ATTITUDE TOWARDS RENEWABLES

An attitude/Green Pricing Survey, looking at renewables in general was conducted. Although the final analysis has not been completed, at the time of writing, initial results indicate that, of the 338 respondents:

1. 79% stated that they would prefer to use renewables over conventional electricity generation
2. 78% felt that the advantages of renewables outweighed the disadvantages
3. 71% strongly agreed that EPE should seek out other sources of energy
4. 32% were dissatisfied with EPE's energy program, 47% were ambivalent and only 21% were satisfied

EPE, as part of its Integrated Resource Planning (IRP) requirement, will also be conducting it's own survey of public opinion this summer. Like neighboring Central and Southwest Inc., they have chosen to conduct "Deliberative Polls" to see what the public wants. It will be interesting to see whether the public's enthusiasm for change is matched by a willingness to absorb the likely extra expense associated with choosing green power.

CONCLUSIONS

A significant wind resource exists close to EPE's existing transmission lines. Considering the length of the transmission lines opportunities exist for line support and for the use of distributed windfarms. Unfortunately wind does not appear to coincide with the utilities summer peak loads and therefore can only play a small role in providing energy during the utility's summer peak in demand. Nevertheless, wind could: reduce the loss of load probability and reduce the need to purchase power during periods of scheduled maintenance; and does offer the potential to save hundreds of thousands of gallons of water and thousands of tons of criteria pollutants for a monthly increase of only 44 cents per average household. This calculation assumes that the costs of a 50 MW windfarm were spread across the whole EPE rate base. If a green pricing option is offered to the public it is likely that much less wind power will be realized at a considerably greater per kWh cost to the individuals who are finally allowed to choose renewables. Furthermore, electricity suppliers who invest now in cleaner sources of power may gain a competitive advantage in the coming world of deregulation, when "today's climate change science, carbon dioxide emissions and environmental health research, becomes tomorrows environmental policy, which will require substantial costs for compliance that will (inevitably) be passed on to the ratepayers" (7). With the documented support for renewables by the majority of the public, in survey after survey all across Texas, it is time that the legislature listened and ordered all utilities to incorporate a reasonable percentage of renewables into their energy mix!

ACKNOWLEDGEMENTS

The funding from the EPA, through the offices of the Center for Environmental Resource Management (CERM) made the project possible. EPE also provided considerable assistance to the project, both through access to information and in subsidizing the mailing costs for the survey. The authors are also grateful to the numerous agencies and individuals who have been supportive of our objectives including among others: NREL, AWEA, Rio Grande Cooperative, SeaWest, Zond, GLO, and SEED.

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THE ROLE OF CAPACITANCE IN A WIND-ELECTRIC WATER PUMPING SYSTEM

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ABSTRACT

The development of controllers for wind-electric water pumping systems to enable the use of variable voltage, variable frequency electricity to operate standard AC submersible pump motors has provided a more efficient and flexible water pumping system to replace mechanical windmills. A fixed capacitance added in parallel with the induction motor improves the power factor and starting ability of the pump motor at the lower cut-in frequency. The wind-electric water pumping system developed by USDA-Agricultural Research Service, Bushland, TX, operated well at moderate wind speeds (5-12 m/s), but tended to lose synchronization in winds above 12 m/s, especially if they were gusty. Furling generally did not occur until synchronization had been lost and the winds had to subside before synchronization could be reestablished. The frequency needed to reestablish synchronization was much lower (60-65 Hz) than the frequency where synchronization was lost (70-80 Hz). As a result, the load (motor and pump) stayed off an excessive amount of time thus causing less water to be pumped and producing a low system efficiency. The controller described in this paper dynamically connects additional capacitance of the proper amount at the appropriate time to keep the system synchronized (running at 55 to 60 Hz) and pumping water even when the wind speed exceeds 15 m/s. The system efficiency was improved by reducing the system off-line time and an additional benefit was reducing the noise caused by the high speed blade rotation when the load was off line in high winds.

INTRODUCTION

More and more wind-electric water pumping systems are replacing mechanical windmills for watering livestock because the electric systems are more efficient, offer the flexibility to site the turbine some distance from the pump, and require low maintenance (Clark and Mulh, 1992). The motors and pumps used in the system are designed for constant rotational speed (rpm) but the wind-electric system operates at variable speed. The output from the wind turbine generator is variable-voltage and variable-frequency; since it operates over a wide range of wind speeds. An advanced, smart controller is needed to maintain stable electrical conditions and improve the system efficiency. Experience of the past ten years with water pumping systems at USDA-Agricultural Research Service (ARS), Bushland, TX, has shown that

systems operate normally when the ratio of voltage to frequency (v/f) of the wind turbine is maintained near the name plate voltage to frequency ratio of the motor (Clark, 1994).

These pumping systems normally begin pumping water at frequencies of 35 to 45 Hz, resulting from a 4.5 to 5.5 m/s wind speed. The wind-electric water pumping system developed by USDA-ARS operated well at moderate wind speeds (5-12 m/s), but tended to lose synchronization in winds above 12 m/s, especially if they were gusty. The wind turbine has an automatic mechanical furling mechanism to turn the rotor out of the wind to control the rotor speed in high wind conditions or when there is no load. Furling, however, generally does not occur until synchronization has been lost and winds must subside before synchronization can be reestablished. The frequency needed to reestablish synchronization is much lower (60-65 Hz) than the frequency where synchronization is lost (70-80 Hz). As a result, the load (motor and pump) stays off an excessive amount of time resulting in less water being pumped and a lower system efficiency.

Using this experience and the v/f ratio principle, a controller based on an 80c52 chip was designed and put into a small wind-electric water pumping system by USDA-ARS and West Texas A&M University-Alternative Energy Institute (WTAMU-AEI) personnel in the spring of 1996 (Clark and Ling, 1996). The controller not only samples the frequency which is used to decide when to connect and disconnect the generator from the motor, but also samples the voltage and calculates the v/f ratio. Any abnormal condition, such as overload, overheating of the generator or loss of one phase of power will drive the v/f ratio below a programmed set point and the controller will disconnect the load and protect the generator and motor from being damaged. This inexpensive controller can be programmed to accommodate a variety of small wind-electric water pumping systems. During the past year, significant improvements were made in the controller design. The improved controller provides a stable system that stays on line and keeps pumping water most of the time, even when the wind speed exceeds 12 m/s by dynamically connecting additional capacitance which keeps the output frequency around 55 Hz and output voltage around 220 volts.

SYSTEM CONFIGURATION

Figure 1 shows the block diagram of the system consisting of a wind turbine, a permanent magnet synchronous generator, a controller, an induction motor, a submersible pump and two banks of compensating capacitance. A fixed capacitance C1 is connected with the motor load and capacitance C2 is dynamically connected at a selected frequency. The generator is directly connected to the induction motor driving the water pump.

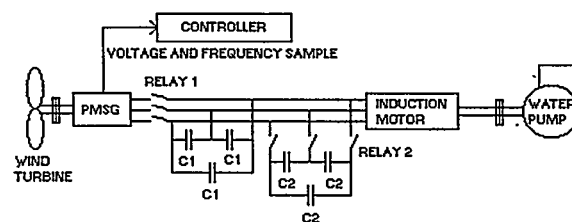


FIGURE 1. BLOCK DIAGRAM OF PUMPING SYSTEM

The system field tested for this study consisted of a wind turbine with a rotor diameter of 2.5 meters, and a generator rated at 850 watts at 12 m/s wind speed. The electric motor was a 0.37 kW submersible induction motor connected to a nine-stage 0.37 kW submersible pump. The output frequency and voltage of the generator were directly proportional to the speed of the wind turbine.

The controller samples voltage and frequency and decides from keyed in set points when relay 1 should be on or off. If the frequency becomes too high due to high winds, relay 2 connects the second bank of capacitors (C2) to consume the additional current thereby maintaining synchronization for an extended wind speed range. Figure 2 is the brief equivalent circuit of the system. The circuit parameters, per phase, are identified as follows:

f	= generator frequency
R_s	= stator winding resistance
E_s	= generator phase voltage
X_s	= synchronous reactance
V_s	= generator terminal voltage
X_{l_s}	= stator leakage reactance
X_{l_r}	= rotor leakage reactance
X_m	= magnetizing reactance
R_r	= rotor resistance
I_g	= phase current
I_s	= motor current
I_c	= capacitor current
I_m	= stator excitation current
I_r	= rotor current

The phase current, I_g is the vector sum of rotor current, I_r and capacitor current, I_c .

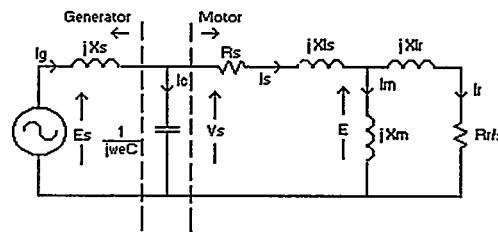


FIGURE 2. SYSTEM EQUIVALENT CIRCUIT

SYNCHRONIZATION

The output torque of the pump is proportional to the square of its rotor speed.

$$T = K_{\omega} \omega_m^2$$

where,

K_{ω} = constant

ω_m = rotor speed of the water pump

The output torque of the motor is proportional to the ratio of generator terminal voltage, V_s , to frequency, f . If the output torque of the motor is greater than the torque needed for the

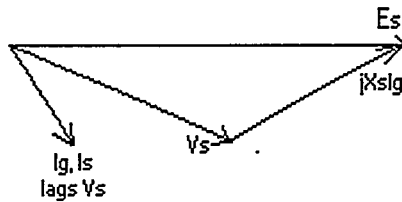


FIGURE 3. PHASOR DIAGRAM WITHOUT COMPENSATING CAPACITANCE

pump, the system will keep synchronization. The motor is running at the slip frequency which is slightly less the generator frequency. When the output torque of the motor is less than the torque needed for the pump, the motor speed slows down or the system will collapse if the frequency of the generator continues to increase at the strong wind condition. A thorough analysis of the interaction of the components of a wind-electric water pumping system is described by (Muljadi, Flowers, Green and Bergey, 1995).

THE ROLE OF CAPACITANCE

Figures 3 and 4 are phasor diagrams showing the effect of compensating capacitance. In Figure 3, the phase current (I_g) is the same as the motor current (I_s) since no compensating capacitance is connected. Since the motor is an inductive load, the motor current (I_s) lags the terminal voltage (V_s). Figure 4 is the phasor diagram when a bank of fixed compensate capacitance ($C1$) is connected in the system. The capacitor current (I_c) leads the terminal voltage (V_s) by 90 degrees. The phase current (I_g) is the vector sum of motor current and capacitor current. By adding the proper amount of capacitance, the terminal voltage (V_s) is increased and the power factor is improved. If the output frequency (f) of the generator stays the same, the v/f ratio will increase and the increased motor torque enables synchronization to be maintained. The controller described in this paper dynamically connected additional capacitance of the proper amount at the appropriate time to keep the system synchronized (running at 55 to 60 Hz) and pumping water even when the wind speed exceeded 15 m/s, a wind speed that usually produces a frequency too high to maintain synchronization. The system efficiency was improved by reducing the system off-line time.

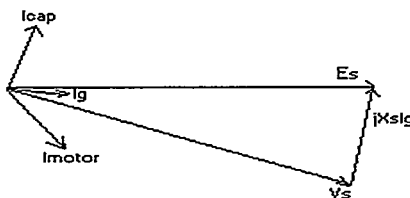


FIGURE 4. PHASOR DIAGRAM WITH COMPENSATING CAPACITANCE

SIZE OF COMPENSATING CAPACITANCE

Figures 5, 6, 7, 8 are plots of the terminal voltage, frequency, voltage to frequency ratio and flow rates relative to wind speed when fixed banks of zero, 20 and 35 μF of capacitance are

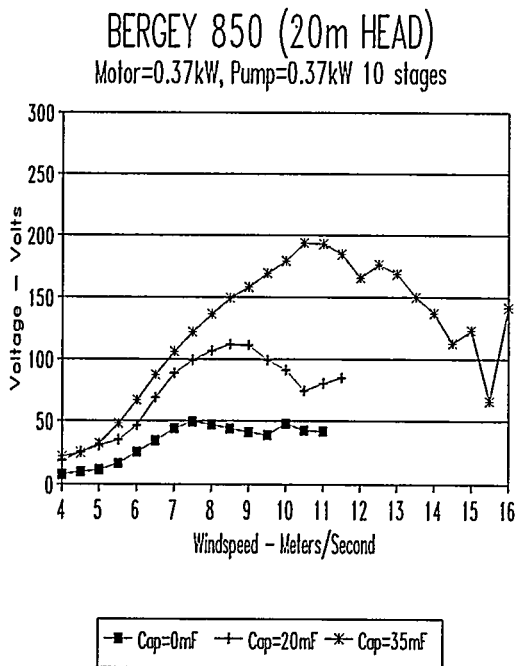


FIGURE 5. EFFECT OF CAPACITANCE ON VOLTAGE FOR A 20 m HEAD.

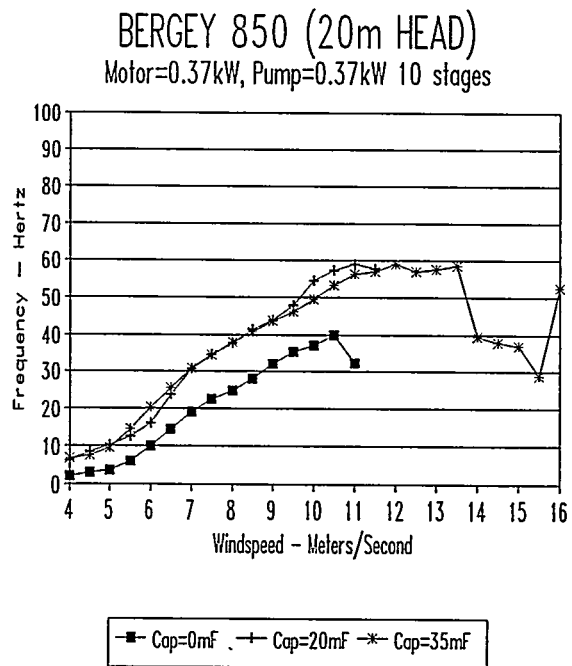


FIGURE 6. EFFECT OF CAPACITANCE ON FREQUENCY FOR A 20 m HEAD.

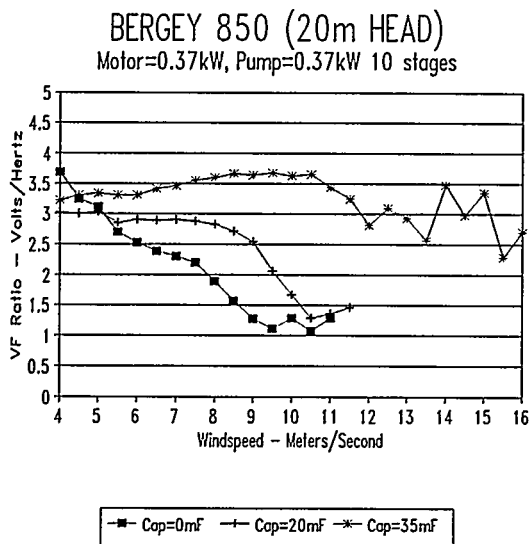


FIGURE 7. EFFECT OF CAPACITANCE ON V/F RATIO FOR A 20 m HEAD.

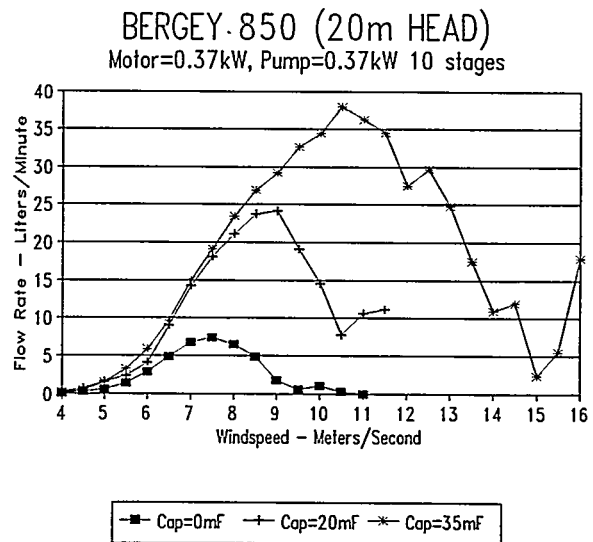


FIGURE 8. EFFECT OF CAPACITANCE ON FLOW RATE FOR A 20 m HEAD.

connected to the system. The motor-pump configuration for the 20 m pumping depth was a 0.37 kW submersible motor with a ten-stage 0.37 kW submersible pump. The torque needed to drive the pump increases as the pump spins faster. The output torque generated by the motor is proportional to the v/f ratio. As shown in Figure 7, the v/f ratio of the system with zero capacitance decreases with increasing wind speeds. When the wind speed reaches 7.5 m/s, the v/f ratio drops to about 2, and the motor torque starts to decline and the pump speed slows resulting in a lower flow rate as noted in Figure 8. With 20 μF capacitance, the system flow rate increases with increasing wind speeds until a wind speed of 9 m/s is reached. When the wind speed goes above 9 m/s, the system has a tendency to lose synchronization because the motor can no longer provide the needed torque to drive the pump. With 35 μF of added capacitance, the system flow rate is even better due to the boost in terminal voltage and higher v/f ratio. The v/f ratio now stays between 3 and 4 with 35 μF of capacitance, which is close to the utility v/f ratio, until the winds reach about 11 m/s. But the possibility of losing synchronization still exists when the wind speeds are above 11 m/s because of the same reason explained above.

There are several disadvantages when the system loses synchronization. The phase current, I_g , goes high if the load (motor) is still connected and could cause the generator or the motor to burn out. The generator terminal voltage goes very high when the load is disconnected and could damage the insulation of the windings of the generator or penetrate the solid state relay used for connecting the load. Additionally, the high rotor speed results in added vibration and noise.

Figures 9, 10, 11, 12, 13, 14 show flow, terminal voltage, frequency, v/f ratio, current and power curves plotted as a function of wind speed. Each figure compares 3 different compensating capacitance scenarios for a motor-pump configuration using a 0.37 kW motor, a 9 stage 0.37 kW pump at a 30 meter pumping depth. The first capacitance scenario is a

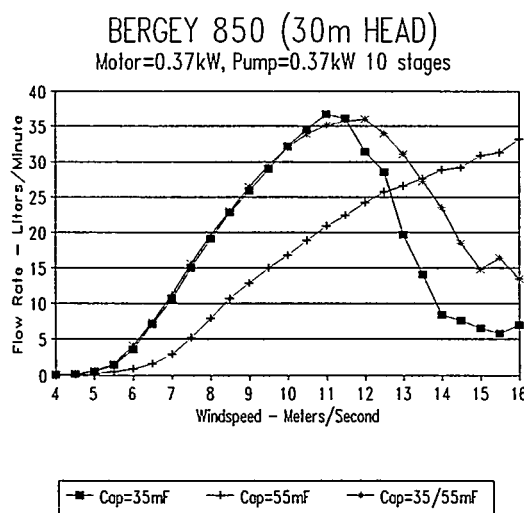


FIGURE 9. EFFECT OF CAPACITANCE ON FLOW RATE FOR A 30 m HEAD.

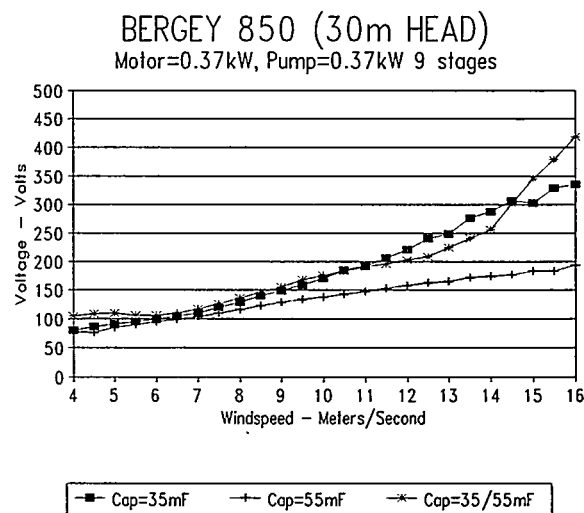


FIGURE 10 EFFECT OF CAPACITANCE ON VOLTAGE FOR 30 m HEAD.

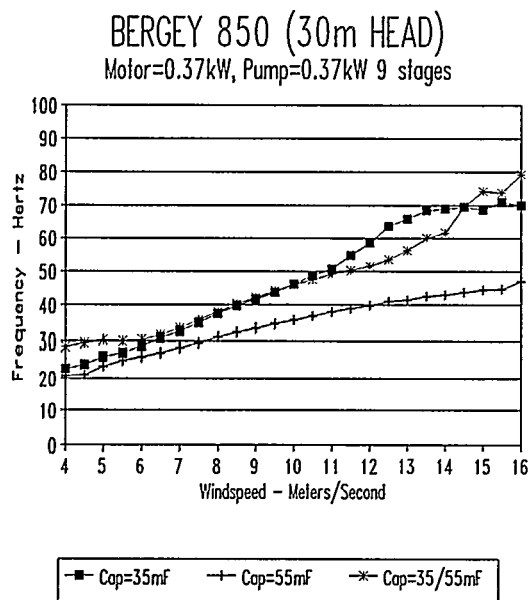


FIGURE 11 EFFECT OF CAPACITANCE ON FREQUENCY FOR A 30 m HEAD.

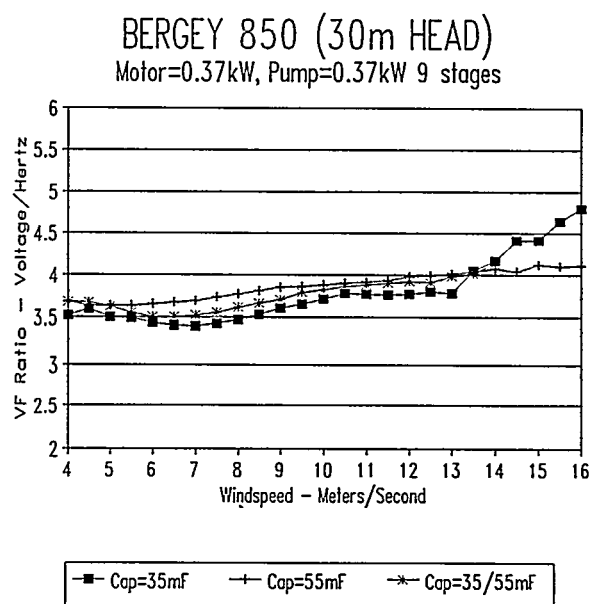


FIGURE 12 EFFECT OF CAPACITANCE ON V/F RATIO FOR A 30 m HEAD.

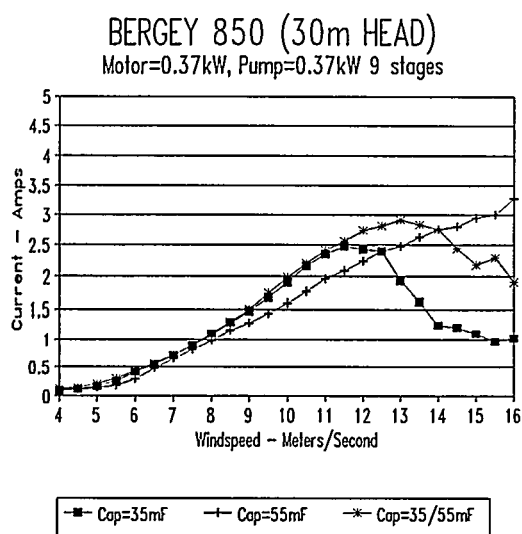


FIGURE 13 EFFECT OF CAPACITANCE ON CURRENT FOR A 30 m HEAD.

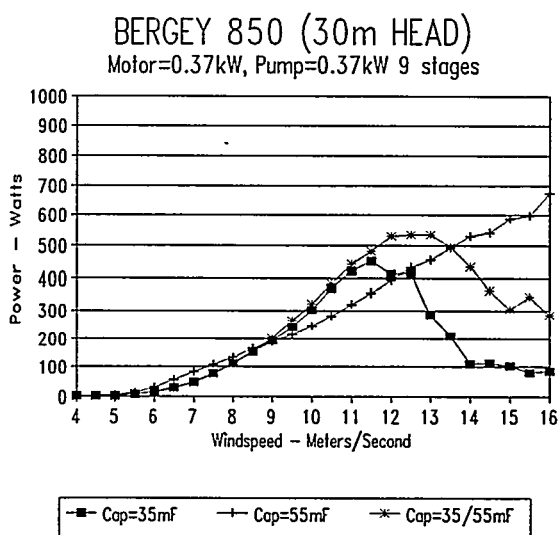


FIGURE 14 EFFECT OF CAPACITANCE ON POWER FOR A 30 m HEAD.

constant 35 μF . As shown in Figure 1, C1 (35 μF) is always connected when the load is connected. The second capacitance scenario is a constant 55 μF , C1 (35 μF) and C2 (20 μF), both always connected when the load is connected. The third capacitance scenario is 35 μF /55 μF , C1 (35 μF) always connected when the load is connected with C2 (20 μF) dynamically added as needed to help maintain synchronization in winds above 11 m/s. The system with fixed 35 μF capacitance works fine if the wind speed stays below 11 m/s. When the wind goes higher, the system loses synchronization and the controller disconnects the load.

The system with a fixed 55 μF capacitance maintained synchronization even when the wind speed reached 16 m/s because of the higher v/f ratio than the system with 35 μF capacitance. The turbine stayed on line and produced 700 watts at 16 m/s wind speed, but pumped considerably less water at low wind speeds which has much more significance for the wind water pumping system. The reduced flow rate is the result of the lower output frequency of the generator causing slower rotational speed of the motor and pump. The reason why Figure 12 shows a higher v/f ratio for the system with 35 μF than with 55 μF capacitance when the wind speed is above 13 m/s is that, after losing synchronization, the controller will disconnect the load, the terminal voltage will increase immediately and cause the v/f ratio to go high (Figure 10).

When the 35 μF /55 μF capacitance is used, the system works as follows: when the wind speed is less than 12 m/s, (system frequency about 55 Hz), a 35 μF capacitance (C1) is already on the system and when the wind speed goes above 12 m/s, an additional 20 μF capacitance (C2) is connected into the system. Figure 9 shows the system with the dynamic connection of C2 and performs as well as the system with fixed 35 μF capacitance at the low wind speeds yet pumps more water at wind speeds above 11 m/s. The wind speed range for a stable system is extended and excessive noise and vibration caused by off line operation in high winds is reduced. We believe the system efficiency can be improved even more at the high wind speeds by varying the duty cycle of the dynamically added capacitance and plan to test this idea in future tests.

Because the system is under dynamic control, the average maximum output power from the generator is increased from 450 watts to 550 watts. A larger sized motor, probably 0.56 kW (0.75 hp), is needed to consume the additional power. Otherwise the motor may be overheated and damaged. A small motor usually works better at the lower wind speeds than a big motor because of the starting torque. The selection of a small motor or big motor is dependent on the wind regime where the pumping system is installed. For the system we presented in this paper, a 0.37 kW (0.5 hp) motor is recommended for wind regime where the average wind speed is less than 7 m/s.

CONCLUSION

Connecting capacitance at the output terminal of the generator can increase the output voltage thereby increasing the voltage to frequency ratio and the torque generated by the induction motor. By using a fixed capacitance, the voltage to frequency ratio is almost constant and the torque is almost constant within the whole wind region. However, since the torque needed to drive the pump is proportional to the square of the rotational speed of the pump, when the frequency reaches a certain point the torque generated by the motor is less than the torque

needed to drive the pump and the system loses synchronization. By putting a relatively large capacitance in the system to draw more current from the generator the electric torque of the generator can be increased but this slows down the rotational speed of the generator and reduces the flow rate since the pump speed is also reduced. If proper control logic is used with a sufficiently fast frequency sample rate and dynamically connecting additional capacitance only when needed, the system will stay synchronized at an extended wind speed range. Under the dynamic control strategy, the generator power output was increased from 450 watts to 550 watts (Figure 14). An added benefit of reducing the off line time is the reduction of noise and guy cable vibration caused by the high speed blade rotation when it is off line in high winds. In order to prevent over heating of the motor at the high output range for a prolonged period, it might be necessary to connect a resistive dump load to maintain the proper v/f ratio.

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COMPUTER CONTROL FOR REMOTE WIND TURBINE OPERATION

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Abstract

Light weight wind turbines located in harsh, remote sites require particularly capable controllers. Based on extensive operation of the original ESI-80, moved to such a location, a much more sophisticated controller than the original one has been developed. This paper describes the design, development and testing of that new controller. The complete control and monitoring system consists of sensor and control inputs, the control computer, control outputs, and additional equipment. The control code was written in Microsoft Visual Basic on a PC type computer. The control code monitors potential faults and allows the turbine to operate in one of eight states: off, start, run, freewheel, low wind shut down, normal wind shutdown, emergency shutdown, and blade parking. The controller also incorporates two "virtual wind turbines," including a dynamic model of the machine, for code testing. The controller can handle numerous situations for which the original controller was unequipped.

Background

With the current movement towards restructuring of the electric utility industry in Massachusetts and throughout the United States, there is widespread interest in distributed, renewables based generation. As a result, there are expected to be a significant number of potential applications for wind turbine installations which will be significantly different from the California wind farms. At least in New England, sites may only be able to accommodate one or a few machines, and they may be in relatively remote and inclement locations. For wind turbines to be used successfully at such sites, they need to be more than just aerodynamically and mechanically suitable for the conditions. They must also incorporate a robust and comprehensive control and monitoring system. Experience gained from the operation of an ESI-80 wind turbine on a high ridge in western Massachusetts has provided the impetus for the design and implementation of a completely new control and monitoring system for that turbine. Development and use of that system has also provided insights into what would be required for a commercial controller.

The original ESI-80 wind turbine, first installed in the Altamont Pass in California, was moved to Massachusetts in 1991 and re-installed on Mt. Tom in Holyoke, MA in 1994. Preparations for the reinstallation and initial operating results are described in Manwell et al. (1993) and Baring-Gould et al. (1995.)

The ESI-80, rated at 250 kW, embodies characteristics common to many of the turbines installed in the California wind farms. It has a horizontal axis, fixed pitch, stall regulated rotor and is connected to an induction generator via a fixed ratio gearbox. It also has some features which are less common, but which result in a high power to weight ratio. The latter include a two bladed, down wind teetered rotor; planetary gearbox; clutch type high speed shaft brake; and aerodynamic tip brakes. The relatively light weight design offers the benefits of ease of installation and low capital cost, which should result in a low cost of energy. On the other hand, light weight can mean increased susceptibility to the unexpected. Consequently, it is imperative that the control system be able to respond quickly and appropriately to any foreseeable situation.

Original ESI-80 Controller

The ESI-80, as originally configured, did not have a comprehensive control and monitoring system. What it did have was a relay based controller, organized according to the rules of ladder logic. This controller was able to start and stop the turbine as the winds rose or fell. It was also capable of stopping the turbine or preventing operation in the event of certain faults. Timers allowed a measure of tuning of the sequencing of events. For example, start up entails latching the tip flaps closed, turning on the air compressor, actuating the brake release solenoids once the compressed air reservoir is full, and connecting the generator to the grid once the brake has released. The relay controller, using the timers, was perfectly capable of sequencing the various steps. Similarly, stopping the turbine involves deploying the tip flaps, disconnecting the generator from the grid, and releasing the air from the brake. Again, the relay controller could carry out that function. Additionally, the turbine would shut down for various electrical faults and if the vibration switch, generator temperature switch, or low air pressure switch were activated.

Limitations of original controller

When the winds are relatively steady, and all components of the machine are functioning as designed, such a controller would be quite adequate. In the presence of a limited number of faults, the controller would also function adequately, as long as there were no sensor failures. Beyond these functions, the capability of such a controller is limited.

Review of the relay controller's capability and initial operation of the turbine in Massachusetts lead to the conclusion that the relay controller would not be adequate to allow the turbine to run unattended. As no remote monitoring and control was possible with the relay controller, it was then decided to operate the turbine only with an operator on site. This decision resulted in fewer operating hours than would have been the case if the turbine were left to run on its own. On the other hand, first hand operating experience highlighted the weaknesses of the controller logic and provided the basis for the development of the new control system. In retrospect, it is clear that the turbine would never have survived in its harsh new surroundings without such an approach.

During operation a number of unexpected events occurred whose adverse effects could have been or minimized or eliminated by use of the new controller or whose adverse effects would have been aggravated by the relay control scheme:

1. Leaky brake seals resulted in decreased brake pressure, causing the brake to drag. A pressure sensor failure with no redundancy allowed the turbine to keep running, damaging the brakes. Manual shut down and repair were required.
2. Leaky brake seals in cold weather delay brake release, aborting starting procedure.
3. Internal seal leaks in the hydraulic teeter dampers resulted in a hydraulic lock, restricting teeter motion and eventually damaging the damper supports. Manual shut down and repair were required.
4. An unexplained electrical event caused the generator to be disconnected from grid during high winds. Manual shut down was required.
5. A gust during turbulent winds caused one tip flap to deploy, requiring a manual shut down.
6. When the wind drops during operation, the turbine may yaw upwind requiring a shut down.
7. Turbine stops with rotor upwind and blades nearly vertical; will not align itself properly, until blades are turned by manual "bumping."
8. When the turbine is not running horizontal wind shear due to the shape of local terrain can cause damaging twisting of droop cables over just a few hours. Manual unwinding and repair is then required.

9. Ice build up in tip flap wells results in imbalance or tip flap deployment. Manual parking of the blades in a horizontal position is required to minimize build up or a shutdown required during operation.
10. Ice build up on blades degrades aerodynamic performance requiring a shutdown.
11. Previous operating history indicated that gearbox bearings might fail, but the relay controller provided no information on the gearbox.

Development of New Controller

After the first winter's operation of the turbine, it became obvious that significant effort needed to be directed to the development of a new controller. That effort included the analysis of possible failure modes, sensor selection, logic design, and computer platform selection.

The process was begun with a Failure Modes and Effects Analysis (FMEA). This analysis, described by Bird (1996), consisted of analyzing plausible failure modes and their consequences for each of the components. The likelihood of the failures and their consequences was then used as a guide in the selection of parameters to be measured and decisions to be made. With the completion of the FMEA, sensors were selected and the required control logic was formulated. The logic approach that was chosen involved a looping process with continual error checking and selection of one of a limited set of operating modes (e.g. start-up, stop with tip flaps, etc.).

The platform that was originally chosen for the signal processing and decision making was a conventional Programmable Logic Controller, manufactured by B&R Corp. Although the PLC approach showed some promise, it still was difficult to implement some of the relatively complex algorithms which, it was becoming apparent, were really needed for the controller to actually meet its design requirements. The final choice for the control and monitoring system was a 486 personal computer. This choice was made because a computer of this type was able to provide all the capabilities and flexibility that the system required, as well as allowing ease of high level, graphical interface based programming.

Description of Computer Control and Monitoring System

Overview

The complete control and monitoring system is illustrated in Figure 1. The system consists of a power supply, sensor and control inputs, the control computer, control outputs, an independent logging computer, and a video system.

All of the computers, sensors, and control circuitry are powered by an uninterruptable power supply (UPS) to insure that any problems with the grid will not affect control of the turbine.

Data is provided to the computer from a number of sensors. Most of the sensors are on the wind turbine itself, although some are located in the control house itself or on a nearby FAA communications tower. Signal conditioning and optical isolation of the signals occurs in the control house. The signals are directed either to an analog to digital (A/D) conversion board or a digital input/output (DIO) board which are located in the computer.

The heart of the system is the control computer ("controller"). The software performs a number of functions, including fault detection, data logging, data display, and remote communication, but the most important function is decision making. In its decision making role, the software continuously analyzes information on the turbine state, looks for problems, and decides whether to take any action to change the operating state of the turbine. The next most important function of the controller is its role in remote communication. At a remote site a second computer (the "caller") can communicate via modem with the controller. This allows a remote operator to monitor and send control commands to

the controller. The controller can also access a pager. The pager is activated when the turbine needs immediate attention (such as unwinding of the droop cable) and is not being monitored by the caller. Meanwhile, the software logs data and displays the sensor output in engineering units on the computer's screen, as well as the state of the control relays.

Control decisions made by the computer logic are converted to commands to the DIO board which controls relays. These relays in turn operate the main relays which provide power to the controlled devices. An additional digital output through the DIO board goes to a circuit external to the computer which causes an immediate shut down of the turbine in the event of failure or freeze up of the controller ("0101 circuit").

The control system also includes a separate logging computer and video system. The additional independent data acquisition system provides summaries of meteorological conditions and wind turbine power. The final item, being installed at the time of writing of this paper, is a video monitor. The picture and sound will be transmitted by microwave to UMass, where they will be displayed and used in conjunction with the caller.

More details on the various features of the control and monitoring system are provided below.

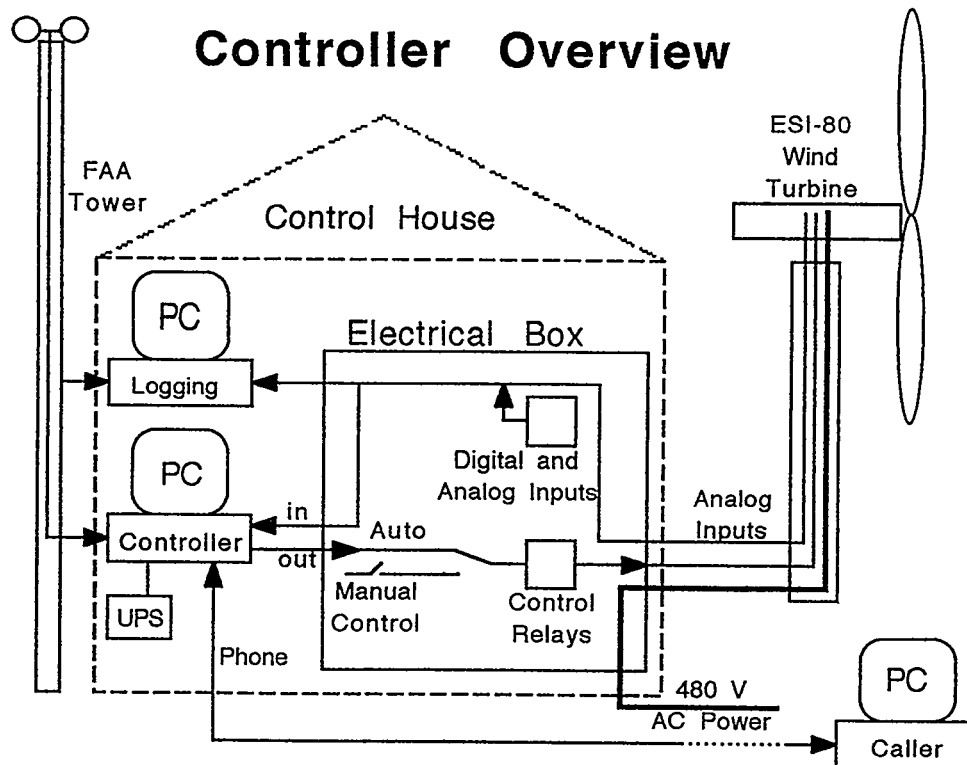


FIGURE 1. OVERVIEW OF CONTROL AND MONITORING SYSTEM

Sensor and Control Inputs

Data used by the controller may come from any of five sources: i) sensors on the wind turbine, ii) sensors in main electrical control box (in the control house), iii) meteorological sensors in the control house or on the FAA communications tower 300 ft away, iv) operator input at the controller, v) remotely generated input from the caller.

Signals from the wind turbine include: i) wind speed at the nacelle, ii) yaw error, iii) air compressor operating state (on/off), iv) brake air pressure, v) brake disc temperature, vi) brake piston temperature

vii) generator temperature, viii) generator rpm, ix) two gearbox bearing temperatures, x) nacelle acceleration, and xi) teeter angle. Signals from the main electrical box include: i) power, ii) current, iii) line voltage, iv) phase fault status, v) voltage fault status, v) starter fault status, and vii) frequency fault status. Signals from the FAA tower which are input to the controller include wind speed and wind direction at the 120 ft height. Ambient air temperature is input from a sensor outside the control house. Operator inputs from the controller include commands to start or stop the turbine, or to park the blades. Inputs from the caller are similar to those at the controller itself, although somewhat more limited.

Controller Outputs

There are six devices ultimately controlled by the computer controller. They are the same devices used with original relay/ladder logic controller: i) tip flap magnets (2 wired in series), ii) air compressor, iii) air tank/brake solenoid, iv) high volume brake solenoid, v) starter/contacter. All of these devices are wired such that may be activated manually or via relays controlled by the computer. A manual switch on the main electrical control box determines which method is available.

One additional control output insures that the turbine will stop in the event of computer failure or software problems. With execution of each loop through the controller, a 0 or a 1 is written to an output port of the DIO board. Should this stop, the "0101 circuit," will shut off a master relay, cutting all power to the controlled devices. Control cannot be restored without operator intervention.

Controller Hardware

As indicated above, the controller itself is based on a 486 personal computer, operating on Windows 3.1. The A/D board is a 32 channel RTI800 board, made by Analog Devices, and the DIO board is a DIO-24 board, made by Computerboards.

Controller Software

The control software was written at UMass, in Microsoft Visual Basic 3.0, Professional Edition (VB). VB was chosen because of its flexibility, its graphical interface and communications capabilities, and because of familiarity with it based on previous experience. In addition, Graphics Server 4.0 software was used to enhance the interface, and the API software Apiguide.dll (Appleman, 1994) was used for reading the A/D and DIO boards.

The control software has three basic parts: i) the control code, ii) a "virtual wind turbine" for controller development and time series simulation, and iii) an input simulator ("virtual wind turbine 2") used for testing the controller's features. The latter two parts were used for development and testing.

Control Code

The control code has six primary functions: i) input processing, ii) range checking/fault detection, iii) selection of operational mode, iv) generation of control commands, v) display of data, vi) data acquisition and vi) remote communication.

The main control procedure involves a loop which is continually accessed while the controller is running. Any or all of the above functions may take be performed during each loop, depending on the inputs and the previous state of the controller. Figure 2 illustrates a flow chart of the main control code functions.

Input Processing

The input processing involves first of all accessing the A/D and DIO boards. Input from the A/D board is first scaled to engineering units. Input from the DIO board may generally be used as is. The digital

values from the A/D board are digitally. Once filtered, some derivative inputs are of interest (such as turbine yaw revolutions or "wraps"), are calculated.

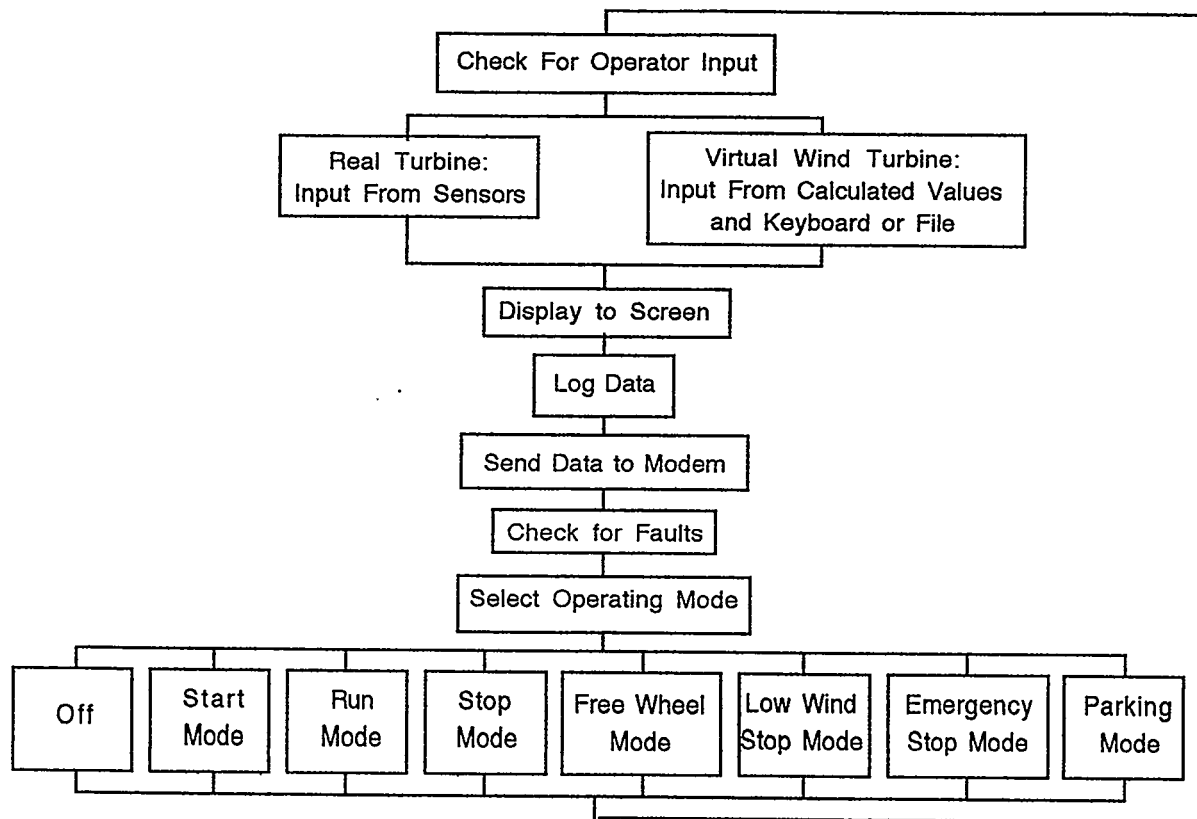


FIGURE 2. CONTROLLER FLOW CHART

Range Checking/Fault Detection

The input data are then all checked to see if they fall within an allowed range (that can be modified by the operator). If an input is outside of the allowed range, the turbine is shut down (if running) or not allowed to start. An operator is required to review the situation and take appropriate action.

Selection of Operational Mode

Once the input data has been checked the controller selects the turbine operational mode. The possible modes are i) OFF ("reset required"), ii) START, iii) RUN, iv) NORMAL STOP, v) FREE WHEEL, vi) LOW WIND STOP, vii) EMERGENCY STOP and, viii) PARKING.

OFF and START Modes - The OFF mode means that the turbine is stopped, and it is not allowed to restart until an operator presses a reset button on the computer screen. Once reset, the controller normally enters the START mode. Before the turbine actually starts, however, a number of conditions must be met. First of all, the wind speed must be above or below specified cut-in values for a prescribed amount of time. Additionally, the yaw error can not exceed another specified value. Once the wind speed and yaw error conditions are met, a starting sequence of events is initiated. The tip flap magnets are energized so that the flaps are latched shut. The air compressor is enabled so that pressure will build up in air tank. Once the tank pressure is high enough that the compressor goes off, the brake is released by activating the solenoids. This is accompanied by an increase in brake piston pressure. Once the controller sees that the pressure is above a specified level, the starter circuitry

("soft-start") is activated, connecting the generator to the grid. This action will result in the turbine motoring up to just over 60 rpm (at the rotor) in about 10 sec.

RUN Mode - After the end of the start up period, the controller enters the normal RUN mode. Activity during this mode involves a full range of error checking (more so than during start up), and continual evaluation of the need to switch to one of the stop or free wheel modes.

NORMAL STOP - If the winds get too high, or if there is another reason for the turbine to shut down (such as instructions to do so from the operator), the controller enters the normal shut down mode. This entails deploying the tip flaps, disconnecting the generator from the grid, and applying the shaft brake. The latter is accomplished by opening and closing the brake solenoids so that pressure drops at first rapidly, and then more slowly. This is done so that the brake begins to apply quickly, but that final application is gentler and less potentially damaging to the turbine. Once the turbine is stopped (as indicated by the rpm signal), the controller may enter the start or off mode, depending on the reason for the shutdown.

FREE WHEEL and LOW WIND STOP Mode - During normal operation, if the winds die down so that generator power drops to a negative value for a specified time, the controller will enter the "free wheel" mode. In this mode, the generator is disconnected from the grid, and the turbine speed is allowed to float. This mode is selected to prevent frequent starting and stopping in light and variable winds, but to still allow some operation during those conditions. In the free wheel mode, if the winds pickup so that the generator rpm exceeds synchronous speed, the generator is reconnected and power is produced again. Conversely, if the wind continues to drop so that the generator rpm falls below a specified level, the controller enters the "low wind stop mode." This entails leaving the generator disconnected, and applying the shaft brake gradually (using only one solenoid valve.) The minimum rpm currently allowed is constrained by the natural frequency of the tower, which corresponds to about 2/3 of the normal operating speed of the turbine. Under some free wheel conditions, the turbine will begin to yaw upwind. The controller monitors the yaw error, and if it exceeds a specified value the controller will also stop the turbine. This prevents the turbine from running in an upwind mode should the winds pick up again, or from wrapping indefinitely if the winds remain light.

EMERGENCY STOP Mode - Under a few conditions, it may be necessary to stop the turbine as quickly as possible and unconditionally. This is accomplished by the "emergency stop mode." Under emergency stop conditions, power is immediately withdrawn from all the control actuators. This means that the tip flaps are deployed, the compressor is turned off, the generator is disconnected from the grid, and both solenoid valves are opened. At the present time, the emergency shutdown mode is entered only if the rotor rpm exceeds a specified value, the brake begins to overheat, or an operator activates the emergency shutdown command.

PARKING Mode - Parking of the rotor entails bringing the blades closer to horizontal. The process involves manipulating the brake solenoids and applying power to the generator for a short amount of time ("bumping"). The turbine may yaw out of the wind if the blades are not horizontal. If the yaw error is too high, the turbine will not be allowed to start. Under these circumstances, the controller bumps the blades to move them to a new azimuthal position and waits to see if the yaw error corrects itself.

Display of Data

Data from all of the analog sensors is displayed on the controller's screen in engineering units. Derived values such as yaw angle and droop cable wraps are also displayed. Check boxes corresponding to the states of various fault sensors and as well as the commanded states of the control relays are present on the screen. Text boxes are provided to display a variety of notes summarizing operating states, fault conditions, status of remote connections, etc.

Data Acquisition

The controller itself is not intended to be a complete data acquisition system. Nonetheless it embodies a substantial data acquisition capability. This data acquisition capability provides a great deal of information about the operation of the turbine and the performance of the controller. Data can be logged in two modes: continuously, and during shutdown events. During normal operation, the controller can write to the computer's hard disc over 25 values as frequently as specified by the operator, up to the speed of the main control loop (which is about 10 times per second). In the case of an unusual event resulting in a shutdown, however, data from immediately before and after the event, collected at the fastest possible rate, is written to the hard disc. The resulting "event files" can be used to examine the causes and effects of the event.

Remote Communication

The communications functions of the controller code include both the capability to communicate with an external computer (the "caller"), allowing remote monitoring and control, and the ability to call a pager. The caller code operates under Windows 3.1 on a remote computer. The controller sends the same data displayed on the controller computer screen to the remote caller over phone lines. The data is displayed on the caller computer screen. Control commands can also be sent from the caller to the control computer. In case of problems, the computer is also programmed to page the on-call turbine operator and send a numeric code stating the condition of the turbine. Currently the number of twists ("wraps") in the cables is sent down to the pager. This method opens up possibilities for other types of notification which have not been explored and are being left to future development.

Response to Unusual Events

Selection of an operational model sometimes involves responding to unusual events, even in the presence of noisy signals. A few of these situations are described below.

If one of the input signals is outside of the allowed range, the controller will shut the turbine down, or prevent it from starting, as mentioned previously. In order to minimize the effect of spurious noise on the signals, a signal can be tested to see if it is outside of its allowed limits for a specified amount of time or fraction of time. For example, low voltage during startup triggers the phase fault detector. If the phase fault ceases within a specified time it is assumed that it is noise related. If it persists, the start up is aborted. The same approach is used for high wind conditions. Thus, for example, a single instance of a wind gust above an upper limit does not result in a turbine shut down, but a sustained wind above that limit does cause a shut down.

A nuisance tip flap deployment is detected by continuously calculating the expected power from the wind speed, using a historical power curve as the basis. A sustained deviation of more than -110 kW, is assumed to be due to a tip flap deployment. Because this is initially assumed to be a nuisance condition, the turbine is allowed to restart. If the condition persists over a number of restarts, the turbine is shut down and an operator reset is required.

Integration of Controller

The control codes has been developed with the help of two software "virtual wind turbines" and field testing. These "virtual wind turbines" allow extensive testing without running the actual turbine by artificially inputting data such as wind speed, power, bearing temperature, rpm, and brake pressure. The testing by simulation was important in finding bugs in the computer program, reducing wear and tear on the real turbine.

The controller code was first developed and tested with the use of a software "virtual wind turbine" (VWT) The virtual turbine was an adapted version of the drive train analysis code, DRVTRNVB,

which was also coded in Visual Basic. That code, the original version of which is described by Manwell et al. (1996), is able to replicate much of the dynamic behavior of the wind turbine, which is of great significance in the sequencing of the controller commands. The program reads in a large wind file and then calculates such things such as rpm, power and brake pressure in response to controller decisions.

For subsequent testing of the code, an input simulator was developed. This simulator, referred to as "virtual wind turbine 2" (VWT2) takes advantage of the graphical interface capability of Visual Basic. To test the reaction of the controller to different events VWT2 uses the keyboard and mouse to increase, decrease or have the computer control the value of variables such as wind speed, power, brake pressure, etc. Thus the controller response to unusual events can be determined.

Testing by simulation was followed and accompanied by an extensive period of field testing. The field tests involved all the available operational modes, and most of the fault conditions. For the latter, input settings available to the operator allowed adjusting the fault ranges for testing without actual operation under fault conditions. Field testing also resulted in fine tuning the controller and revealed the need to add some new features.

Illustration of Controller Function

Illustrations of the controller's capability during field operation are shown in Figures 3-5. Figure 3 shows the controller shutting down the turbine due to the power being more than 110 kW below the expected power. In this case one of the two tip flaps had deployed (probably by a gust of wind), causing the power to drop. Detecting this, the controller disconnected the generator and deployed the other tip flap before applying the shaft brake. Figure 4 shows the turbine going into free wheel mode when the wind speed is low and the generator starts motoring. The generator is then disconnected from the grid and the rotor rpm starts to drop. After the wind speed and then the rpm rise, the generator is reconnected. (If the wind speed had continued to drop, the turbine would have shut down.) Figure 5 shows a high wind shutdown. The criteria for a high wind shutdown in this case was if the wind was above 50 mph for an integrated 30 seconds in a 900 second period or if an instantaneous value was greater than 60 mph. Figure 6 illustrates a normal turbine starting procedure. Once the brake pressure reaches a predetermined level, the soft start connects, limiting the generator current to 1000 amps as the turbine accelerates.

Summary and Conclusions

Initial operating experience with the ESI-80 at a New England ridge top site revealed that the original controller was inadequate for the conditions encountered there. The conditions of particular significance- extreme cold, ice, wind shear, turbulence, and directional effects- are not unique to that site and, in fact, will appear in varying degrees in many sites with complex terrain and/or cold climates. A new computer based control system, designed to address those conditions, has shown itself to be far more capable of responding appropriately to those conditions than was the original controller. The hardware for the new control system is relatively generic, in that it is based upon a conventional personal computer. The software control logic, however, is quite comprehensive and flexible, allowing addition of progressively more intelligence as required. The implications of experience with this controller suggest that relatively light weight and mechanically simple wind turbines such as the ESI-80 may be suitable for difficult sites, but only if they include a comprehensive and intelligent control and monitoring system.

Acknowledgments

We would like to acknowledge the financial and material support of the Massachusetts Division of Energy Resources, Analog Devices, O'Connell Energy Group, and the nearby Mt. Tom Ski Area.

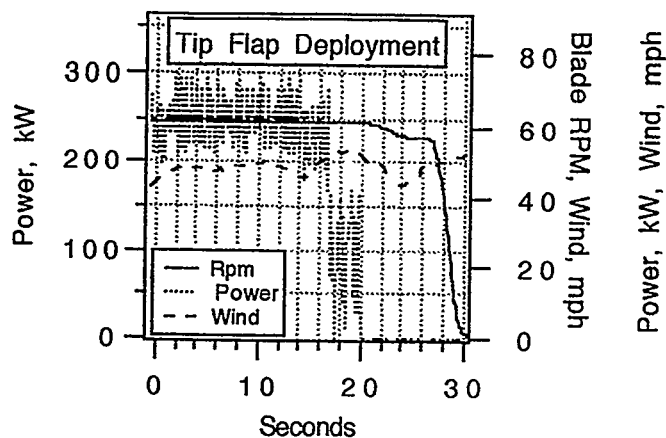


FIGURE 3. TIP FLAP DEPLOYMENT

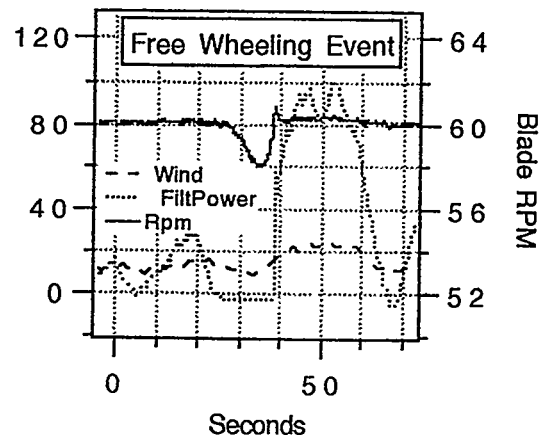


FIGURE 4. FREE WHEELING

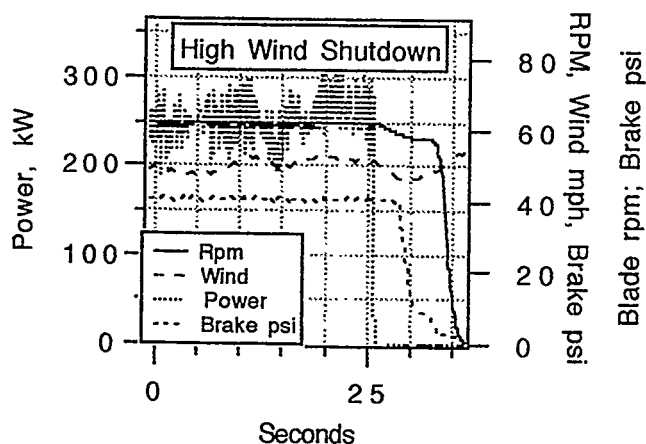


FIGURE 5. HIGH WIND SHUTDOWN

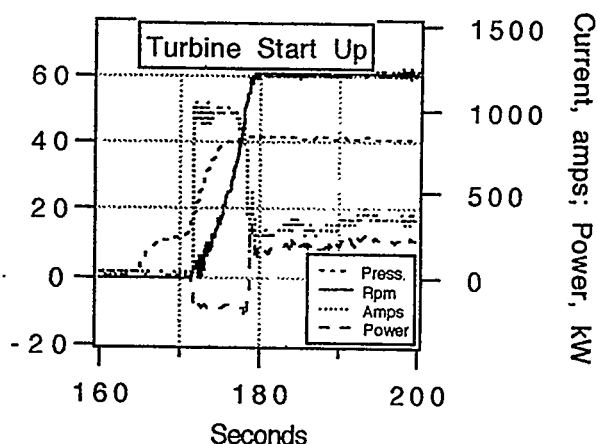


FIGURE 6. TURBINE START UP

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INDUCTION GENERATOR-INDUCTION MOTOR WIND-POWERED PUMPING SYSTEM

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INTRODUCTION

The energy storage matter plays an important role in wind-electric conversion systems for isolated applications. Having that in mind, two different approaches can be basically considered: either the immediate conversion of the generated electric energy, as in a water pumping system or electric energy storage for later use, as in a battery charging system.

Due to some features such as no need of an external reactive power source and, sometimes, a gearbox, permanent-magnet synchronous generators have been broadly used in low rated power isolated systems. Despite that, system performance can be affected when the generator is feeding an inductive load (e.g., an induction motor) under variable-speed-variable-frequency operational conditions. Since there is no effective flux control, motor overload may occur at high wind speeds. Thus, good system performance can be obtained through additional control devices which may increase system cost.

Although being rugged and cheap, induction machines always work as a reactive power drain; therefore, they demand an external reactive power source. Considering that, reactive static compensators appear as an attractive alternative to the *cost x performance* problem [1]. In addition to that, different control strategies can be used so that system performance can be improved.

In this work, an isolated small wind electric pumping system using induction machines with static reactive power compensation is studied. Indirect vector control of the machine's stator flux is used to determine its instantaneous compensator current values in order to improve power flow while machines operate at variable speed and variable frequency.

The system is composed of a generation unit (windmill - induction generator) which directly feeds a pumping unit (induction motor - centrifugal pump) and a reactive power static compensator connected to the AC bus between induction machines. System configuration can be viewed in Figure 1.

Hysteresis control of the converter switches is employed, resulting in a variable frequency harmonic content of compensator current waveforms. A capacitor and a start up battery bank are connected to the DC link of the converter allowing stand-alone operation of the system. The electrical connection between the compensator and the machines is done through coupling inductors to reduce current rates.

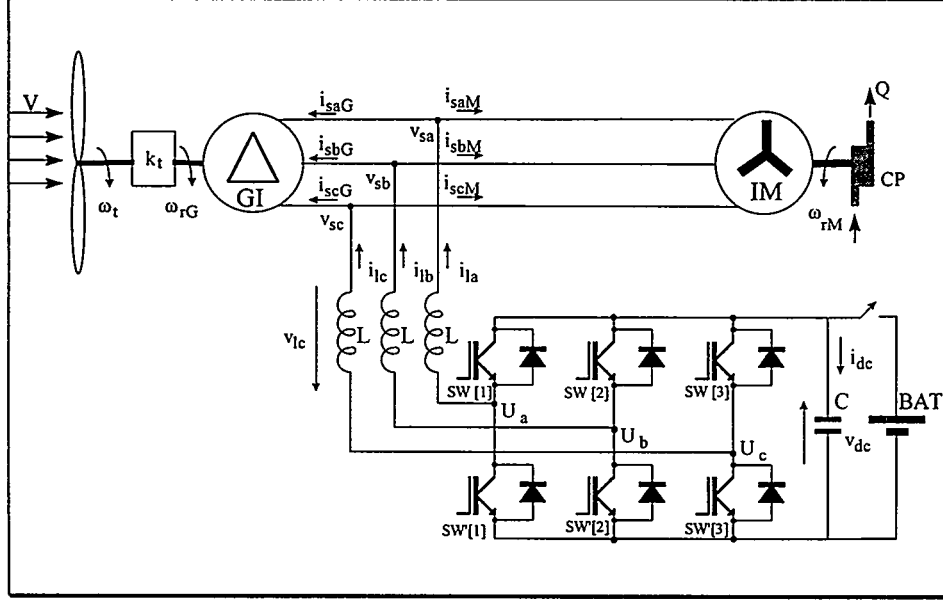


FIGURE 1: SYSTEM CONFIGURATION

Power flow is such that the reactive power used to magnetize the induction machines is controlled by the compensator and a small amount of real power flows from the generator to the DC link capacitor. A stator-flux-based indirect vector control strategy is used to determine the magnetizing (d-axis) current reference i_{dl}^* . The capacitor charge (q-axis) current reference i_{ql}^* is calculated aiming at keeping the DC capacitor charged at a determined voltage V_{DC} . Considering that this voltage must be high enough to impose the current references into the AC bus and the generator stator voltage is approximately proportional to its speed, a control scheme is used to keep V_{DC} proportional to the generator speed, avoiding high switching frequencies and thus reducing the harmonic content of compensator currents.

The adopted indirect vector control strategy is based on the orthogonality (Eq. 1) between the generator back e.m.f. vector ($\vec{E}_g$) and the stator flux vector ($\vec{\varphi}_{sg}$). To establish the orientation reference axis, the generator back e.m.f. vector and the electrical frequency are replaced by the generator stator voltage vector $\vec{V}_s$ and its rotational frequency ω_{rg} , respectively. Therefore, a stator voltage vector reference frame is used [2].

$$\vec{E}_g = j\omega_{eg} \vec{\varphi}_{sg} \quad (1)$$

The instantaneous position of stator voltage phasor (θ_V) is calculated from its module $|\vec{V}_s|$ and its stationary components, $V_{s\alpha}$ and $V_{s\beta}$, which in turn are obtained from the three-phase values (V_{sa} , V_{sb} and V_{sc}), as showed in Eq. 2:

$$\cos(\theta_V) = \frac{V_{s\alpha}}{|\vec{V}_s|} \quad \sin(\theta_V) = -\frac{V_{s\beta}}{|\vec{V}_s|} \quad (2)$$

Instead of a feedforward control of the stator flux through a fixed value magnetizing current i_{dl} , a feedback control loop is used to determine which value of i_{dl} must be imposed to the generator. The feedback loop is composed of a PI controller that uses the generator instantaneous stator voltage vector amplitude and a reference voltage to calculate the reference magnetizing current. The reference voltage is calculated using the generator rated V/f ratio and its speed. The q-axis current i_{ql} is used to control the capacitor voltage, keeping it proportional to the generator speed. A block diagram of the control loop can be seen in Figure 2. Variables marked with a star stand for reference values.

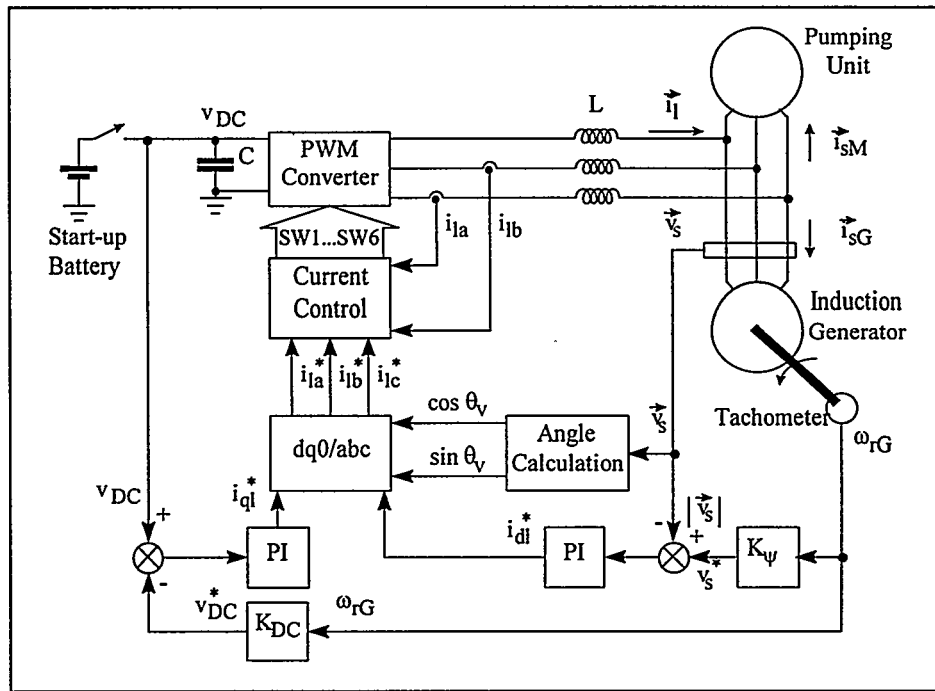


FIGURE 2: CONTROL STRATEGY SCHEME

SYSTEM SIMULATION

A good idea of system operational ranges as well as components efficiency, yearly output and cost effectiveness of the whole system can be given through the use of system steady state simulation. Initially, each distinct part of the system was modeled and simulated. Afterwards, system steady state simulation was carried out.

The wind turbine parameters used in the simulations were taken from Silva [3]. It is a three bladed horizontal axis turbine and a passive variable pitch control method is used to prevent machines from overloading under high wind speed conditions. Machines overloading preventing action of turbine pitch control is showed in Figure 3, where generator and motor power, P_{eg} and P_{em} respectively, become approximately constant for wind speeds slightly greater than 11 m/s.

Water pumps fixed-speed characteristic curves are generally given in catalogs, but if variable speed is used, experimental tests must be carried out to determine its parameters. Figure 4 shows the simulated *water flow x speed* characteristic of the pumping unit. Simulation parameters used were taken from Mourão F^o [4].

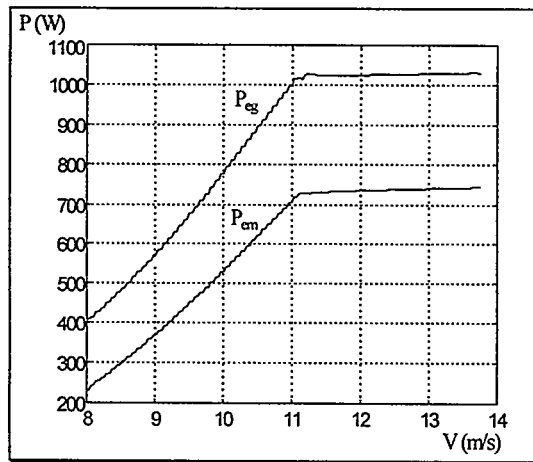


FIGURE 3: INDUCTION MACHINES POWER

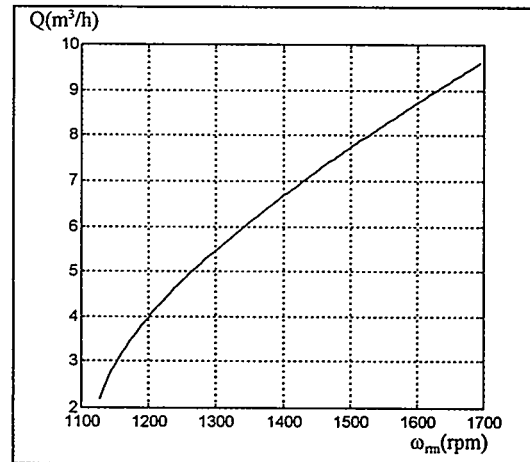


FIGURE 4: WATER FLOW

The effect of induction machines magnetic circuit saturation was considered. For such, an airgap based model was developed for each machine equations set. Machines experimental magnetizing curves were taken and replaced by 11th. order polynomial functions.

For simulation purposes, the static compensator was replaced by a variable equivalent capacitor (C_{eq}), since its charging is not considered under steady state operation. The magnetizing current provided by the capacitor is supposed to be approximately constant due to the V/f control scheme. Thus, the value of the capacitor is inversely proportional to the electrical frequency of the AC bus squared, i.e. $C_{eq} \propto 1/\omega_e^2$. This characteristic is shown in Figure 5. Machines stator flux behavior at different points of operation (generator speed - % rated) is seen in Figure 6.

After that, system dynamic model was obtained and its simulation carried out. Dynamic simulation analysis is an important step for controllers design as well as for assessing system behavior under some transient situations as generator speed variation.

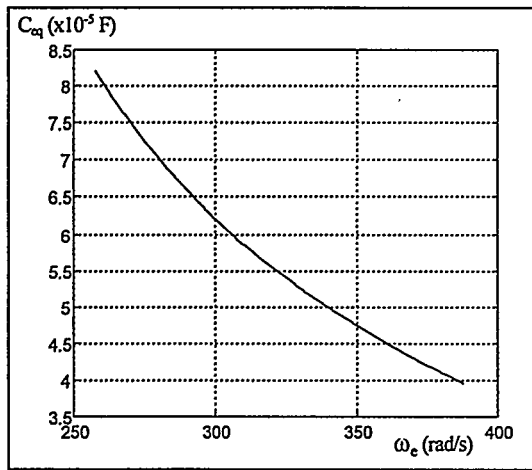


FIGURE 5: COMPENSATOR STEADY-STATE EQUIVALENT CAPACITOR

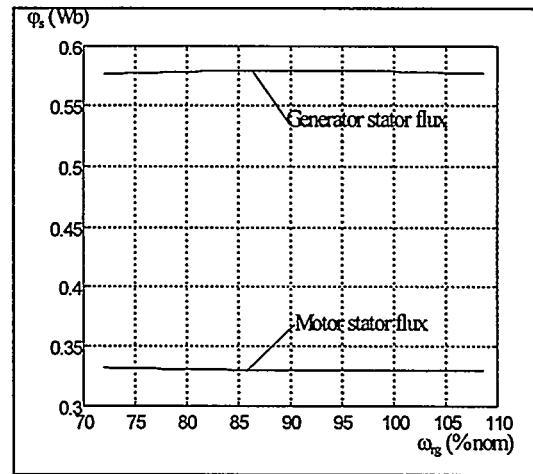


FIGURE 6: INDUCTION MACHINES STATOR FLUX

Due to the high wind turbine inertia, a generator speed transient was simulated having its speed as an input to the system. Figure 7 shows a comparison of generator stator flux and the motor stator flux under a speed transient where the generator is accelerated from 1200 to 1800 rpm at $t = 3.0$ sec. The capacitor voltage curve and its reference are shown in Figure 8, indicating the dependence between generator speed and capacitor voltage reference.

It can be seen from Figure 7 that both machines stator flux values are kept approximately constant even using a control strategy based on a scalar control method. Therefore, during speed transients, changes in the active power flow may cause perceptible changes in the magnetic flux. Even so, stability is maintained, mainly considering that real speed transients would not be so fast due to the wind turbine rotor inertia.

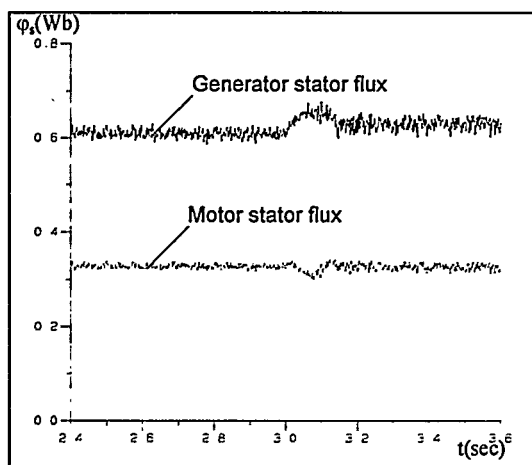


FIGURE 7: INDUCTION MACHINES STATOR FLUX

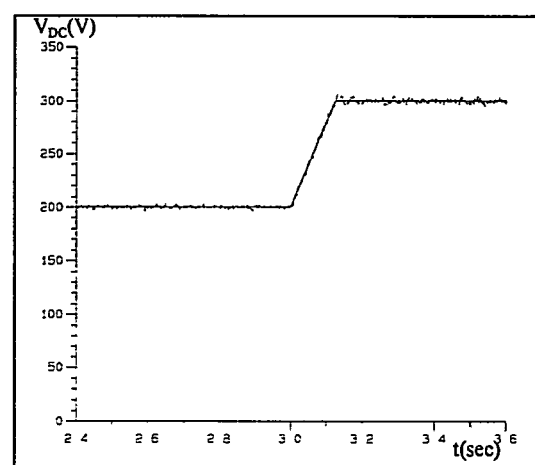


FIGURE 8: DC LINK CAPACITOR VOLTAGE

EXPERIMENTAL RESULTS

A laboratory prototype was built in order to verify system viability and assess its performance. A DC motor was used to drive the generator during experimental tests. After proper conditioning, variables were measured by a data acquisition board with a sampling frequency of 4 kHz. A PC computer was used to run the control algorithm as well as manage data acquisition and generate current references.

The electric connection between machines was done through an auto-transformer (ratio 1:1) to simplify motor start up procedure during the tests. The auto-transformer resistive and leakage voltage drop effects were not significant to be considered in computer simulation.

Initially, a generator speed transient test was carried out by varying the DC motor speed. As shown in Figure 9, the generator is accelerated from 1200 to about 1650 rpm. The flow meter used has a sinusoidal wave with amplitude and frequency proportional to water flow as output signal. A peak detector was implemented in the control algorithm program to determine instantaneous water flow. Since no signal filtering was used, water flow measurements quality were not good. The water flow (m^3/h) during generator speed transient is showed in Figure 10.

As previously mentioned, the control strategy is based on an indirect flux control method which aims at keeping generator V/f ratio constant. Since generator rotational speed ω_{rg} is used instead of its electrical frequency ω_e , i.e. the slip frequency is not considered, the V/f ratio adopted is slightly smaller than the rated one.

Figure 11 shows the compensator DC link capacitor voltage and its reference for the same generator speed variation, pointing out its dependence with speed. A similar characteristic can be viewed in Figure 12, where generator stator voltage and its reference (rms values) are presented.

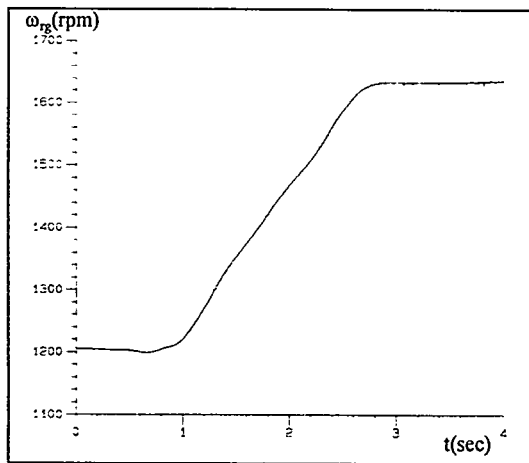


FIGURE 9: GENERATOR SPEED

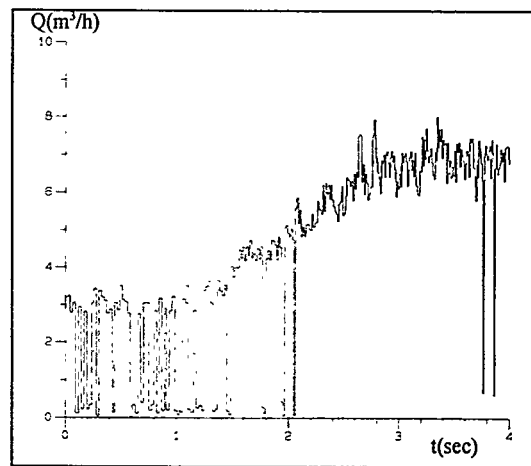


FIGURE 10: WATER FLOW

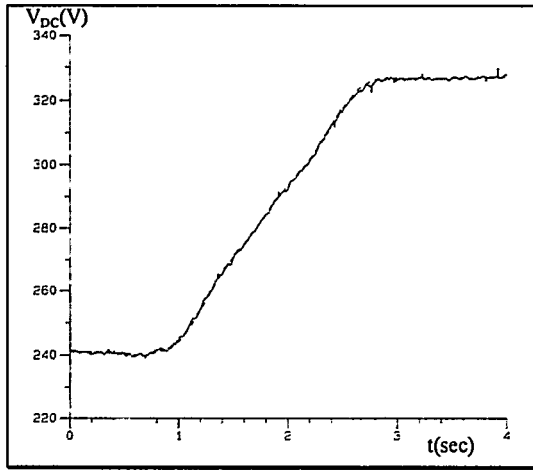


FIGURE 11: DC LINK CAPACITOR VOLTAGE AND REFERENCE

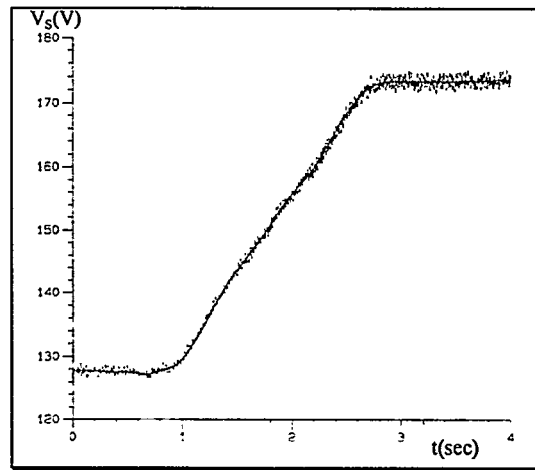


FIGURE 12: GENERATOR STATOR VOLTAGE AND REFERENCE

Experimental steady state points of operation were taken at different generator rotational speeds by storing one set of variables for each speed. In Figure 13 and Figure 14, measured variables are plotted with a star (*), while reference values are represented by a full line. The DC link capacitor voltage and its reference can be viewed in Figure 13, showing a constant 0,2 ratio between generator speed and DC voltage. Generator stator voltage is showed in Figure 14. As mentioned before, the V/f ratio used in the prototype is smaller than the rated one, thus at 1800 rpm generator voltage is not the rated value (220 V_{rms}).

The water flow as a function of motor speed is plotted in Figure 15. In spite of flow measurement quality, good agreement with the simulated result showed in Figure 4 was obtained.

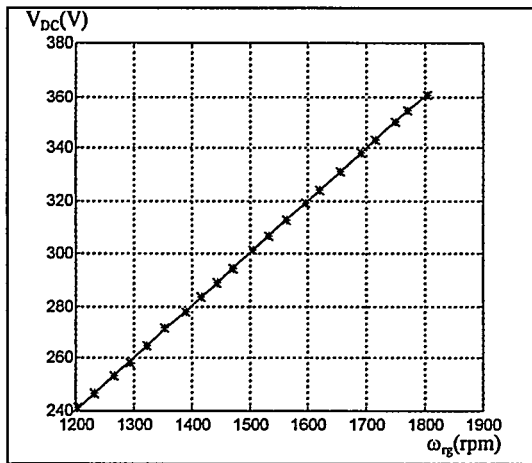


FIGURE 13: STEADY STATE DC LINK CAPACITOR VOLTAGE AND REFERENCE

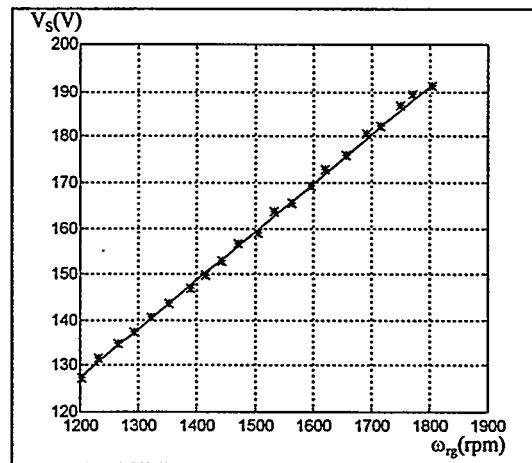


FIGURE 14: STEADY STATE GENERATOR STATOR VOLTAGE AND REFERENCE

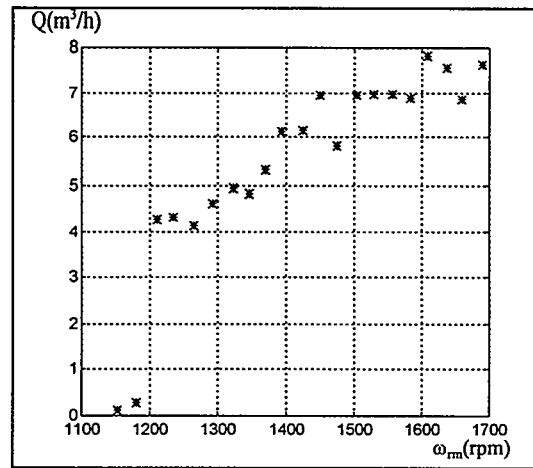


FIGURE 15: WATER FLOW

CONCLUSIONS

A variable-speed variable-frequency wind electric pumping system comprising induction machines was presented. A stator voltage vector based indirect vector control method of generator stator flux through a PWM compensator was proposed and assessed through digital simulation and experimental tests.

Steady state and dynamic system simulation results were taken. Control strategy effectiveness in keeping nearly constant flux operation was demonstrated. Experimental tests were carried out aiming at validating theoretical studies. At first, experimental results are in agreement with the simulation ones, motivating further studies including system efficiency, costs, output under a determined wind regime as well as system stability analysis and development of optimization criteria.

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A MATHEMATICAL LOOK AT A PHYSICAL POWER PREDICTION MODEL

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ABSTRACT

This paper takes a mathematical look at a physical model used to predict the power produced from wind farms. The reason is to see whether simple mathematical expressions can replace the original equations, and to give guidelines as to where the simplifications can be made and where they can not. This paper shows that there is a linear dependence between the geostrophic wind and the wind at the surface, but also that great care must be taken in the selection of the models since physical dependencies play a very important role, e.g. through the dependence of the turning of the wind on the wind speed.

1 INTRODUCTION

Over the past five years interest in and need for models that can predict the power produced by wind farms have emerged. This is mainly because there now exist many areas where the penetration of wind energy is so large that fluctuations in the wind-energy-produced power affect the control and dispatch at the electrical utility. Basically two different types of models have appeared: physical (cf Landberg et al, 1993, and Barbour and Walker, 1995) and statistical (cf Jensen et al, 1994). Both types of models have their own virtues, the physical models can accurately predict far into the future and statistical model accurately predict events in the near time horizon. It follows from this that a model combining these two approaches will predict accurately in the near-term (-6 hours) as well as the long-term (-40 hours). Combined models are described elsewhere at this conference (Landberg, 1997b). This paper will venture into the border-land between the two types of pure models. It will zoom in on the equational basis of the physical model and derive simple relations that replace the original ones. The short-comings of these simple relations are also analysed. The paper will briefly describe the physical model, it will then move on to analysing the different sub-models and finally the total simplified mathematical model will be presented.

2 THE PHYSICAL MODEL

The method for predicting the power output of a wind farm is outlined in Figure 1. The idea is to use physical models as 'far' as possible, this is done such that the large-scale flow is modeled by a NWP model, here HIRLAM (Machenhauer, 1988); as we zoom in on the site - using the geostrophic drag law and the logarithmic wind profile - more and more detail is required, this detail is provided by the WASP program (Mortensen et al, 1993). To take the shadowing effects of turbines in a wind farm into account the PARK program (Sanderhoff, 1993) is used. Finally, to take any effects not modeled by the physical model and general errors of the method into account

a model output statistics (MOS) module is used. For a more detailed description of the model, see Landberg, 1997a and Landberg and Watson, 1994.

In the analysis that follows only the sub-models based on physical reasoning will be studied, ie the MOS 1 and MOS 2 sub-models are left out.

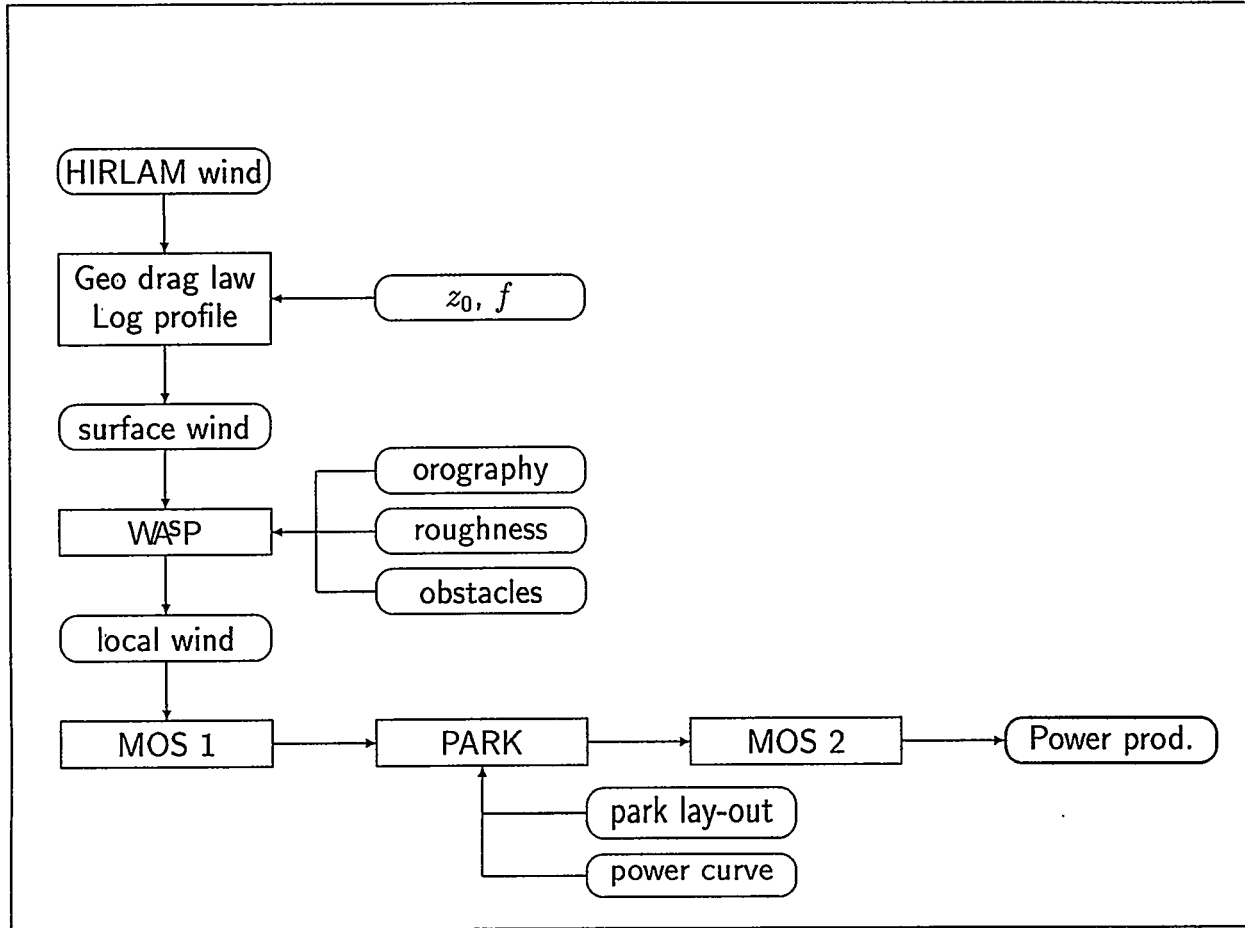


Figure 1: Flow chart outlining the model. The input is a large-scale wind (HIRLAM wind) and the output is the power production of a specific wind farm at a specific time.

3 Analysis of model

The meteorological input to the model is the forecast wind from a numerical weather prediction (NWP) model. This wind is taken as representing the geostrophic wind, $\vec{G}$.

To transform $\vec{G}$ to the surface two equations are used: the geostrophic drag law

$$G = \frac{u_*}{\kappa} \sqrt{\left[\ln \left(\frac{u_*}{f z_0} \right) - A \right]^2 + B^2} \quad (1)$$

and the logarithmic wind profile

$$u(z) = \frac{u_*}{\kappa} \ln \left(\frac{z}{z_0} \right) \quad (2)$$

where u_* is the friction velocity, κ the von Karman constant, f the Coriolis parameter, z_0 the aerodynamic roughness length, A and B are constants and $u(z)$ is the wind speed at height z .

We collapse the two equations by writing the surface wind u as

$$u = (G, \theta, z) \quad (3)$$

since the roughness, z_0 , is a function of direction, θ .

The local corrections calculated by WASP result in a set of direction dependent scaling factors one for each sector, $w(\theta)$, hence

$$w(\theta)u(G, \theta, z) \quad (4)$$

The production for each of the turbines is found by use of the power curve function, pow

$$\text{pow}(w(\theta)u(G, \theta, z)) \quad (5)$$

The total wind farm production, P_{tot} , is given by

$$P_{\text{tot}} = p(\theta)N\text{pow}(w(\theta)u(G, \theta, z)) \quad (6)$$

where $p(\theta)$ is a direction dependent factor taking the shadowing effects of the wind farm into account, and N the number of wind turbines.

Studying the variation of u , cf. Figure 2, it can be seen that given the roughness and height the relation is virtually linear, this leads to

$$u(G, \theta, z) \approx g(\theta)G \quad (7)$$

The total production can now be written as

$$P_{\text{tot}} = p(\theta)N\text{pow}(w(\theta)g(\theta)G) \quad (8)$$

Assigning

$$A(\theta) \equiv p(\theta)N \quad (9)$$

and

$$B(\theta) \equiv w(\theta)g(\theta) \quad (10)$$

the total production can be rewritten

$$P_{\text{tot}} = A(\theta)\text{pow}(B(\theta)G) \quad (11)$$

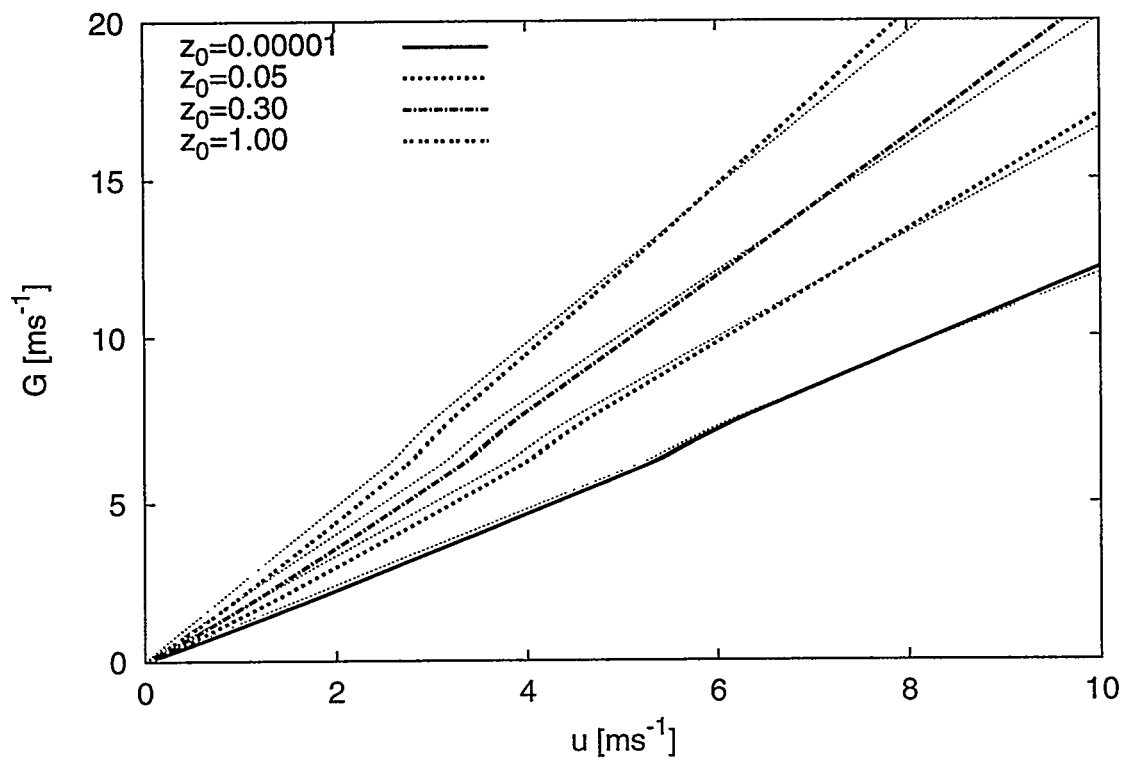


Figure 2: The relation between the geostrophic wind, G , and the wind at the surface, u for different values of the roughness z_0 . A straight line (dotted) is plotted for each roughness value.

This equation states that for a given roughness and height there is a very simple relation between the wind farm power output and the geostrophic wind resembling in essence a power curve function, cf Figure 4. Since all wind-farm-power-prediction cases are related to a specific wind farm both the height and the roughness for a specific sector are constant.

A brief summary of the calculations is given in Figure 3.

	Forecast HIRLAM	→	$\vec{G}$
→	Surface transformation Geo. drag + log. profile	→	$u(G, \theta)$
→	Local corrections WASP	→	$w(\theta)u(G, \theta)$
→	Production	→	$N_{\text{pow}}(w(\theta)u(G, \theta))$
→	Park influence PARK	→	$p(\theta)N_{\text{pow}}(w(\theta)u(G, \theta))$

Figure 3: Summary of the derivation of the simple relation between the geostrophic wind, G , and direction θ .

3.1 Direction

Turning now to the direction, the geostrophic drag law also describes how the wind is turned for the free atmosphere to the surface

$$\alpha = \frac{-B}{\sqrt{\left[\ln\left(\frac{u_*}{fz_0}\right)\right]^2 + B^2}} \quad (12)$$

this equation is plotted in Figure 5, where the angle is plotted against the wind at the surface (using Eq. 1). As can be seen the turning of the wind is highly dependent on the *magnitude* of the surface wind, the direction can change more than 30 degrees. Another problem is that the biggest changes are found in the 0 to 10 ms⁻¹ range, ie the range where most wind speeds for wind energy applications are found.

4 Conclusion

The paper has shown that it is possible to write the very complicated physical relation between the geostrophic drag law and the production of a wind farm as a simple expression resembling in essence the power curve function. The only assumption is that the geostrophic drag law can be approximated by a linear function. One problem that can not easily be addressed by simple relations is the problem of finding the turning of the geostrophic wind, this relation is not simple.

To give some general guidelines to simple-model-constructors, it is fine to develop a simple relation for the power production but treat the direction with care. When estimating the parameters in

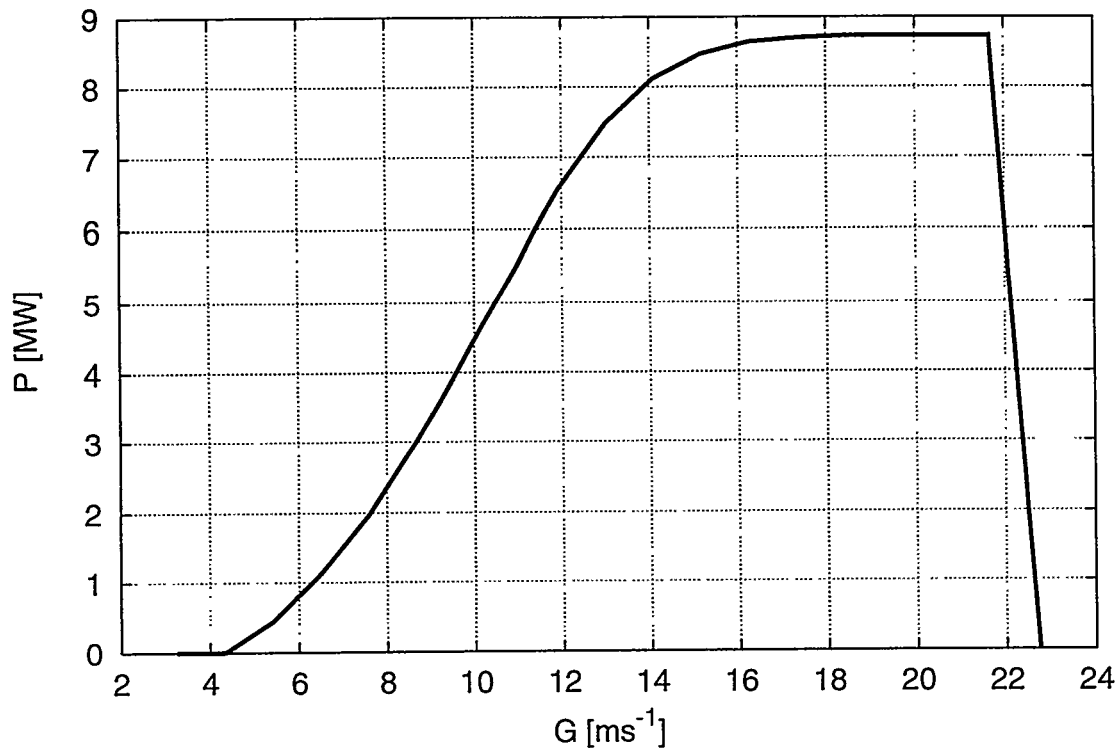


Figure 4: The relation between the geostrophic wind, G and the total production of a wind farm, P_{tot} . The wind farm in the example consists of 15 600 kW machines, the local corrections amount to 1.3 and the park efficiency for this direction is 0.97.

the model, one must ensure that sufficient data (ie data that cover the full range of wind speed, direction and atmospheric stability expected for the site) is available for the estimates to be robust.

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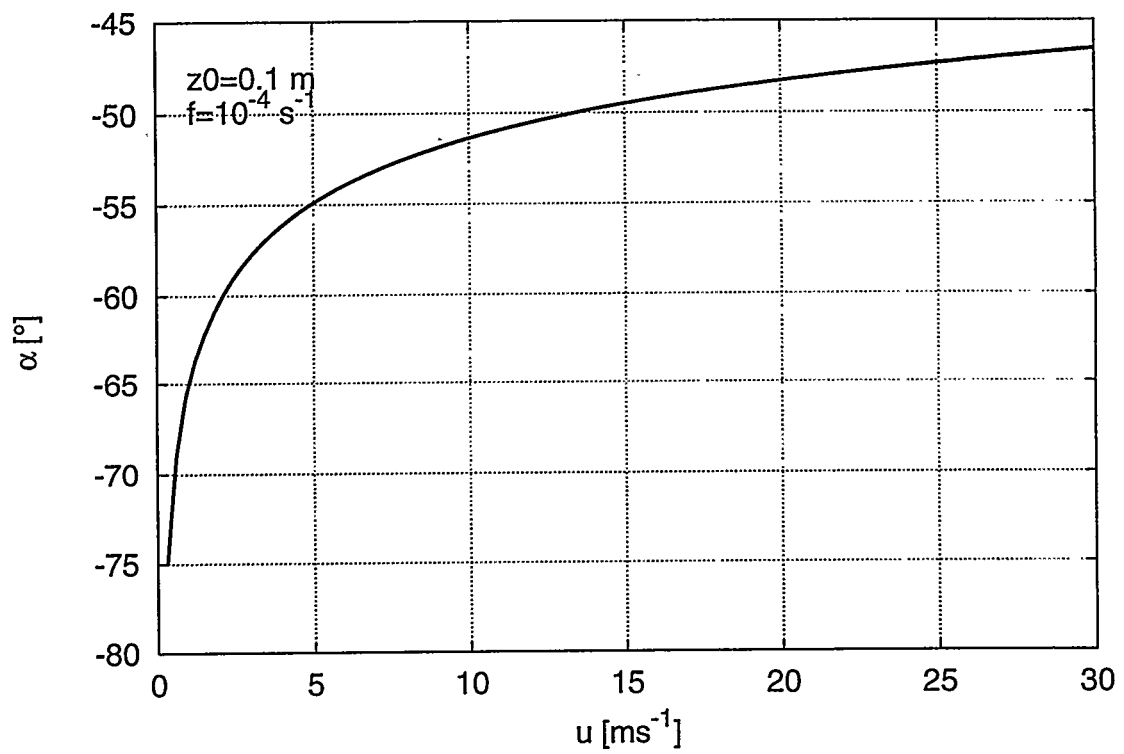


Figure 5: The dependence of the turning of the geostrophic wind on the geostrophic wind speed represented by the surface wind.

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