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Final Technical Report

IEA Wind Task 24

Integration of Wind and Hydropower Systems

Volume 1: Issues, Impacts, and Economics of Wind and Hydropower Integration

iea wind

IEA Wind Task 24 Integration of Wind and Hydropower Systems

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Authors: Tom Acker, Northern Arizona University on behalf of the National Renewable Energy Laboratory
U.S. Department of Energy Wind and Hydropower Program

Prepared for the International Energy Agency Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

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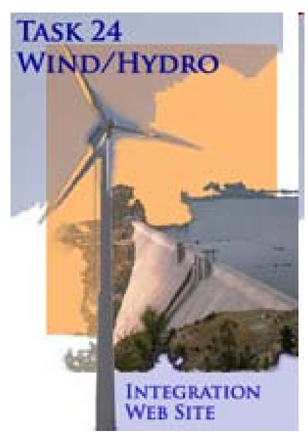
Preface

In November 2003, the International Energy Agency (IEA) Implementing Agreement (IA) for Cooperation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind) held Topical Expert Meeting #41 on the Integration of Wind and Hydropower Systems. This meeting convened a group of industry, academic, and government officials with expertise in wind power, hydropower, and utility and transmission system planning and operation. Their purpose was to discuss the potential for coordinated operation of wind and hydropower in serving load, the benefits and detriments in doing so, and to identify the related opportunities and issues. As a result of this meeting and interactions with the IEA Hydropower IA, a recommendation was made to IEA Wind to establish a formal research task to address the myriad of questions and unresolved issues pertaining to the topic. Subsequent to this meeting, in 2004 IEA Wind established a research and development task to investigate the potential for integrating wind and hydropower resources on the electrical grid. The research task, also known as an "Annex," was the twenty-fourth such task established by IEA Wind, and was entitled: "Task 24: Integration of Wind and Hydropower Systems." Seven member countries of IEA Wind joined the task: Australia, Canada, Finland, Norway, Sweden, Switzerland, and the United States. When established, a research and development (R&D) task is assigned an "Operating Agent" (i.e., managing director). For Task 24, the National Renewable Energy Laboratory (NREL) in the United States, on behalf of the U.S. Department of Energy, was selected as the Operating Agent.

The primary purposes of Task 24 were to conduct cooperative research concerning the generation, transmission, and economics of integrating wind and hydropower systems, and to provide a forum for information exchange. The former of these two purposes was addressed through case study projects performed at participating institutions within each member country. The latter purpose related to information exchange was accomplished via a series of collaborative R&D meetings, seven of which were held: a kickoff meeting (February 2005 in the United States); one web meeting (June 2006); and five R&D meetings (September 2005 in Switzerland, September 2006 in Australia, May 2007 in Italy, September 2007 in Norway, and June 2008 in Québec, Canada).



The Task 24 Final Report summarizes and presents the results of the work conducted by the task participants, the important issues and analysis methods identified, and the related conclusions. The report was assembled in two volumes: the first providing objectives, background, summary results, and conclusions; and the second describing the methods of study employed and details about the participant case studies upon which the conclusions of the task were drawn.

Acknowledgments

Many organizations and people contributed to the Task 24 final report via contributions to the various case study projects conducted by the participants, more than can be acknowledged here. Thanks are due to all these people. Special recognition is due to the following contributors for their participation in the task, its meetings, for oversight of their country's contributions to the case studies, and for organizing their contributions to this report:

United States
Tom Acker, Ph.D., Northern Arizona University, Operating Agent representative on behalf of NREL, primary author and editor
Mr. Robert Zavadil, EnerNex Corporation
Mr. Brian Parsons, National Renewable Energy Laboratory
Mr. Cliff Murley, Sacramento Public Utility District
Mr. Keith Knitter, Grant County Public Utility District
Ms. Patricia Weis-Taylor, PWT Communications, LLC, Secretariat IEA Wind

Australia
Marian Piekutowski, Ph.D., Hydro Tasmania
Mr. Mike Underwood, Hydro Tasmania

Canada
Ms. Simone Lelande, Natural Resources Canada
Mr. André Robitaille, Hydro Québec
Mr. Tom Molinski, Manitoba Hydro

Finland
Hannele Holltinen, Ph.D., VTT Technical Research Centre
Juha Kiviluoma, Ph.D., VTT Technical Research Centre

Norway
Mr. John Olav Tande, SINTEF Energy Research
Mr. Magnus Korpås, SINTEF Energy Research
Mr. Terje Gjengedal, Statkraft

Sweden
Lennart Söder, Ph.D., KTH Swedish Royal Institute of Technology
IEA Hydropower Implementing Agreement
Mr. Niels Nielsen, Kator Research, Secretary of IEA Hydropower IA

List of Acronyms

AEMO	Australian Energy Market Operator
AGC	Automatic Generation Control
BA	Balancing Area
ELCC	Effective Load Carrying Capacity
FCAS	Frequency Control Ancillary Services
HVDC	High-Voltage Direct Current
IA	Implementing Agreement
IEA	International Energy Agency
IEA Wind	The IEA Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems
MAE	Mean Absolute Error
MISO	Midwest System Independent Operator
NREL	National Renewable Energy Laboratory, U.S. Department of Energy
NordPool	The Nordic Power Exchange: The Single Power Market for Norway, Denmark, Sweden, and Finland
NWP	Numerical Weather Prediction
O&M	Operations and Maintenance
PNCA	Pacific Northwest Coordination Agreement
PUD	Public Utility District
R&D	Research and Development
RMSE	Root Mean Square Error
RTO	Regional Transmission Organization
SINTEF	The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology
TSO	Transmission System Operator
U.S.	United States
USACE	U.S. Army Corps of Engineers
VTT	Technical Research Centre of Finland
WAPA	Western Area Power Administration

Executive Summary

This report is the first of a two-volume set. It describes the background, concepts, issues, and conclusions related to the feasibility of integrating wind and hydropower, as investigated by the members of IEA Wind Task 24. It is the result of a four-year effort involving seven member countries and thirteen participating organizations. The companion report, Volume 2, describes in detail the study methodologies and participant case studies, and exists as a reference for this report.

Worldwide, hydropower facilities possess a significant amount of installed electric generating capacity. IEA statistics indicate that at the end of 2001 there was in excess of 450,000 MW of installed capacity within IEA member countries, with about half in Europe and half in North America. In addition to conventional hydropower, there is more than 80,000 MW of installed pumped-hydro capacity in IEA countries. In contrast, utility-scale wind power is relatively new in the electric market, but increasing rapidly. In 2003, when the topic of Task 24 was initially being discussed, there was just over 31,000 MW of wind power installed, an amount that increased to in excess of 140,000 MW by the end of 2009. Competitive costs, coupled with the fact that wind is a clean energy resource, make wind energy capacity likely to continue to grow substantially over the next two decades. Because of the potential for synergistic operation of wind and hydropower facilities, many countries are investigating the opportunity to integrate wind and hydropower systems in order to optimize their output through coordinated operation.

The hope is to realize such benefits as lowering the cost of ancillary services required by wind energy by taking advantage of the built-in energy storage hydro facilities, the opportunity to more effectively utilize existing hydro and transmission facilities, and the potential for improving hydrologic operations, as well as to develop an overall energy supply portfolio that is more diverse, robust, and cleaner. With wind power penetrations increasing worldwide, the topics of Task 24 are more relevant than ever.

For the reasons described above, in 2004, IEA Wind formed research and development Task 24,[1] titled "Integration of Wind and Hydropower Systems." The primary purposes of this Task are to conduct cooperative research concerning the generation, transmission, and economics of integrating wind and hydropower systems, and to provide a forum for information exchange. The following are specific goals of Task 24:

Goal 1) Establish an international forum for exchange of knowledge, ideas, and experiences related to the integration of wind and hydropower technologies within electricity supply systems.

Goal 2) As it pertains to wind and hydropower integration, share information among participating members concerning grid integration, transmission issues, hydrological and hydropower impacts, markets and economics, and simplified modeling techniques.

[1] It is worth noting here that the topics of the task were discussed and the objectives formed through conversations with the IEA Hydropower IA, and formation of a joint task (i.e., sponsored by both IAs) was seriously considered. Though a joint task did not materialize, the collaboration strengthened the work plan of the task and the robustness of the analysis and conclusions.

Goal 3) Through information sharing and exchange of ideas, identify technically and economically feasible system configurations for integrating wind and hydropower, including the effects of market structure on wind-hydro system economics with the intention of identifying the most effective market structures.

Goal 4) Document case studies pertaining to wind and hydropower integration, and create an on-line library of reports.

Task 24 member countries and participating organizations are listed in Table 1. Case studies that analyze the feasibility, benefits, detriments, and costs of specific wind-hydro integration projects were the mechanism through which the goals of the task were addressed and the feasibility of wind-hydro integration was investigated. The general nature of each type of case study is described below.

Grid Integration Case Studies

System balancing is one of the primary functions performed by a transmission system operator. *Ancillary services* is the term generally used to describe the services or functions related to the operation of a balancing area within an interconnected electric power system necessary for maintaining performance and reliability. These services can be broadly categorized as operational reserves or contingency reserves. Operational reserves are generally used to respond to fast fluctuations in total system net load as well as the more gradual and more predictable ramps in net load (*net load* is defined herein as the system load less wind power, or in other words the net load that must be served by the remaining generation fleet). Contingency reserves are generation resources, some fast-responding and synchronized, and some off-line that can be brought on-line and synchronized relatively quickly (within 10- to 30-minutes, depending on the system), used to cover unexpected losses in generation or transmission resources. Grid integration studies are frequently aimed at determining the increase in operational and contingency reserves, and their related costs, caused by the variability of wind power and uncertainty in its prediction.

The wide variety of hydropower installations, reservoirs, operating constraints, and hydrologic conditions combined with the diverse characteristics of the numerous electrical grids (balancing areas) provide many possible combinations of wind, hydropower, balancing areas, and markets, and thus many possible solutions to issues that arise. Hydro generators typically have very quick start-up and response times and may have flexibility in water-release timing. Therefore, hydro generators could be ideal for balancing increased ancillary service requirements due to wind energy fluctuations or even for novel system balancing products such as energy storage and redelivery. Studying grid integration of wind energy, particularly on grids with hydropower resources, will help system operators understand the potential for integrating wind and hydropower resources.

Table 1. Task 24 member countries, contracting parties, and participants

Country	Contracting Party	Participant
Australia	Australia Wind Energy Association	Hydro Tasmania
Canada	Natural Resources Canada	Natural Resources Canada Manitoba Hydro Hydro Québec
Finland	TEKES National Technology Agency in Finland	VTT
Norway	Norwegian Water Resources and Energy Directorate	SINTEF Energy Research Statkraft Energy
Sweden	Swedish Energy Agency	KTH Swedish Institute of Technology
Switzerland	Swiss Federal Office of Energy	EW Ursern
United States	U.S. Department of Energy	National Renewable Energy Laboratory Grant County Public Utility District Sacramento Municipal Utility District Northern Arizona University

Six of the seven countries participating in Task 24 have contributed at least one case study of this nature, covering a wide variety of system configurations, with some representing small systems (<1,000 MW peak load), such as Grant County Public Utility in Washington State, United States, to large systems (>74,000 MW peak load) such as Nordic system. There is also a wide variety of hydropower facilities, with some being essentially run-of-the-river with little storage capacity (a day or two), to very large hydro plants with multi-year storage capability.

Hydropower Impact Case Studies

Depending on the relative capacities of the wind and hydropower facilities, wind integration may necessitate changes in the way hydropower facilities operate in order to provide balancing, reserves, or energy storage. These changes may affect operation, maintenance, revenue, water storage, and the ability of the hydro facility to meet its primary purposes. Beyond these potential changes, integration with wind could potentially provide benefits to the hydro system related to water storage or compliance with environmental regulations (e.g., fish passage) and create new economic opportunities. Thus, the purpose of these case studies was to increase understanding of the impacts and benefits of wind integration on other aspects of the hydropower system. Three of the seven countries participating expect to contribute to these studies.

Market and Economic Case Studies

While grid integration and hydrologic impact studies may demonstrate the technical feasibility of integrating wind and hydropower systems, implementation will often depend on the economic feasibility of a given project. Such economic feasibility will depend on the type of electricity organization or market in which the wind and hydro projects are considered. Addressing economic feasibility in the electricity market will provide insight into which market types are practical for wind-hydro integration, as well as identify the key factors driving the economics. This understanding may provide opportunities to devise new methods of scheduling and pricing that are advantageous to wind-hydro integration and permit better utilization of system resources. These market and economic case studies address the effects of today’s market structures on wind-hydro system economics with the intention of identifying the most effective market structures. Economic studies that consider the value of wind energy generation and hydropower to the electricity customer are of the greatest interest. Because economic feasibility is germane to integrating wind and hydropower, six of the seven participating countries contributed to these studies.

Results of the Task

Though specific wind-hydro integration projects may differ substantially, there are many characteristics common to each. Consequently, there was ample opportunity for each participant of the task to leverage one another's case study projects to enhance their own findings, discuss difficulties faced in analysis and interpretation of results, and debate methods and conclusions. By the end of 2009, six Task 24 participant meetings had been held, as displayed in Table 2. The purpose of each of these meetings was similar: to collaborate on ideas and methods used in studying wind and hydropower integration, and to communicate, interpret, and sometimes debate the methods and results related to specific case studies.

As a part of this process, a common template for describing and interpreting participant case studies was developed, in order to overcome some basic differences in terminology as well as to place the study results in the context of the assumptions, the characteristics of the electrical balancing area, the wind and hydropower generation, the load, and the other generation resources. This common template is described in detail in Volume 2 of this report.

Table 2. R&D meetings of Task 24, including date, location, and host

Meeting	Location / Host	Date
Kickoff	Hoover Dam, NV, U.S. / NREL, USBR, APA	February 22–23, 2005
R&D #1	Lucerne, Switzerland / EW Ursern	September 30, 2005
R&D #2	Launceston, Tasmania, Australia / Hydro Tasmania	September 25–26, 2006
R&D #3	Milan, Italy / EWEA	May 7, 2007
R&D #4	Oslo, Norway / Statkraft	September 19–20, 2007
R&D #5	Québec City, Québec, Canada / Hydro Québec	June 5–6, 2008

A summary of conclusions drawn related to each context of wind/hydro integration are provided below.

Grid Integration Impacts and Costs

Wind power data from existing wind power plants can provide a good indication for the order of magnitude and frequency of wind power output changes with which a system operator or planner must deal. The data suggests that there will be a relatively small impact at the regulation (minute-to-minute) time scale, but becoming considerable at the hourly time scale and beyond (e.g., load following, unit commitment, reserve requirements), especially at high levels of wind penetration. In addition to being variable, wind power is also uncertain, and though accurately predictable much of the time, can suffer from large forecast errors that may occur at inopportune times during system operation. Wind power, while primarily an energy resource, does have a capacity value that should be considered in system planning. What makes wind power different to a system operator and planner as compared to other power resources is its variability and uncertainty, and learning how to understand and work with these characteristics. The overall impact of the wind power variations, forecast errors, and their associated integration cost, combined with the cost of wind energy, its marginal value, and the positive benefits it brings to the electrical system, depend upon a host of factors including the system load, the generation fleet, operational and market flexibility, etc., and can only be accurately estimated via a thorough detailed simulation of the power system. Seven case studies of this task addressed wind integration impacts and costs, the relevant conclusions of which are summarized below.

- Finnish Case Study #1: This study showed that even with the limited flexibility of hydropower (run-of-the-river with small reservoirs), a large part of wind power forecast errors can be provided for by shifting hydropower back and forth inside one day. The study also showed that when correcting the forecast errors of wind power at a large balancing market in which hydropower produces most of the balancing (like in Nordic countries), there is no great benefit from combining/integrating wind power and hydropower at a single producer. It is more cost effective to bid all flexibility of hydropower to the balancing market and use it from there to correct the system imbalances than to use it for dedicated balancing of wind power.
- Finnish Case Study #2: The study analyzed wind power energy penetrations of 10%, 20%, and 30% in the Nordic system (74,000-MW peak load), with the intention of determining whether or not there is enough regulation available from the hydropower to deal with incremental increase in net power system variations and forecast errors due to wind power. The study identified a practical system configuration of 60% of electricity from hydropower, most of which is reservoir hydropower, and 30% of electricity from wind power. Results showed that a large part of hydropower capacity should be capable of flexible operation and able to provide the additional regulation required due to the high penetration of wind power.
- Norwegian Case Study #1: This case study analyzed a regional power system with an assumed 420-MW power transfer capacity. With regard to integrating wind energy, the most conservative approach allows for only 115 MW of wind power in the constrained network with 420 MW of capacity, as this will not require any control actions even in the very unlikely case of maximum wind and hydro generation (115 MW + 380 MW) at the same hour as the historically lowest consumption (75 MW). The results of the study showed that for the specific system under consideration, up to 600 MW of wind power is possible—without noticeable reduction in income from energy sales compared to an ideal non-congested case—by applying coordinated operation of the wind power and hydropower plants.
- Norwegian Case Study #2: This case study considered the impact of wind power on system adequacy and assessed using data from a real-life, regional, and hydro-based power system. Three cases were considered: the installed wind power is 62 MW (Case B) and 1,062 MW (Case A and Case C), which correspond to wind power penetration levels of 1.6% (Case B) and 28.1% (Case A and Case C). The annual load is 21,024 GWh, which gives wind energy penetration levels of 0.9% (Case B) and 15.2% (Case A and Case C). The study concluded that wind power will have a positive effect on system adequacy in a regional hydro-based power system. Wind power contributes to reducing the loss of load probability and to improving the energy balance. Adding 3 TWh of wind or 3 TWh of gas generation are found to contribute equally to the energy balance, both on a weekly and annual basis. Both wind

and gas improves the power balance. The capacity value of gas is found to be about 95% of rated, and the capacity value of wind about 30% at low-wind energy penetration, and about 14% at higher wind penetration.

- Swedish Case Study #2: The aim of the simulation in the second Swedish case study was to study the possibility of balancing wind power in northern Sweden using hydropower in northern Sweden. The simulation included a total installed capacity of 795 MW of wind power, and that output was scaled to 1,000; 4,000; 8,000; and 12,000 MW. All hydropower stations larger than 10 MW in the studied area were considered (i.e., 154 hydropower plants with a combined capacity of 13.2 GW), which corresponds to about 80% of the installed capacity of all hydropower in Sweden. The conclusion of the study was that the existing hydropower in northern Sweden has sufficient installed capacity and is fast enough to balance even large amounts of wind power. The model predicted spill to occur, but, to an overwhelming extent, such a spill can be avoided by using efficient tools, especially for season planning. Only in a few cases—and then in particular for a wind power expansion of 12,000 MW—will there be spill that depends on insufficient balancing capability in the hydropower.
- U.S. Case Study on the Missouri River: The case study on the Missouri River analyzed wind integration into the balancing area operated by the Western Area Power Administration (WAPA) and supplied by hydropower facilities located along the Missouri River. This study considered integrating five levels of wind power penetration of 3%, 3.7%, 9.3%, 18.6%, and 37%. The hydropower capacity is 2,400 MW from six hydro facilities containing multiple years of water storage, and the peak system load was 2,700 MW. The statistical study concluded that in the WAPA system, significant operational impacts from wind energy—those that must be dealt with in planning and operation (regulation, load following, system ramping of net load)—will likely arise when the wind penetration approaches 500 MW (about 18% of the peak system load).
- U.S. Case Study Sacramento Municipal Utility District: This case study focused on hydropower resources along the upper American River and operated by the Sacramento Municipal Utility District. Hourly simulation cases were completed for at least one full year of data for four proposed wind generation penetration levels: 102 MW, 250 MW, 450 MW, and 850 MW. These correspond to the following wind penetration levels (computed by dividing wind capacity by system peak load): 2.7%, 6.7%, 12.1%, and 22.8%. The study found lower penetrations of wind generation have only a small impact on fast regulation requirements, but begin to dominate as the penetration increases. Wind integration costs were computed to range from about $2 to $8/MWh of wind energy produced. The results show a very substantial reduction in operating cost and integration costs with the hypothetical Iowa Hill pumped-storage facility operating (as much as $5/MWh). Furthermore, the results also show that integration costs decrease with increasing diversity of wind generation assets.

Hydropower Impacts

Hydropower generators are inherently flexible, but in practice their flexibility depends on a host of factors. The type and magnitude of ancillary services and reserves that can be provided by a hydropower plant depends on whether it possesses significant storage or if it is a run-of-the-river plant with limited storage. The flexibility of operation also depends on whether or not the hydropower is part of a cascade of dams on a river system, and the level of coordination between those on the same river. Hydro facilities often have numerous functions—power generations being one—that guide their operation and define their flexibility. Layered on top of the physical and functional planning, there may be numerous organizations and stakeholders involved, along with differing market or economic situations. It is the interaction of the many functions, system configurations, and stakeholders that establish the authority, priority, and economics that govern the potential for wind and hydro integration.

The overarching question for studying wind and hydropower integration is whether system-operating impacts due to wind power can be accommodated by hydropower within the constraints currently in place on hydropower (or not easily changed), and in an economically advantageous way. And if so, what changes will this cause to hydropower operations or costs? In concept, hydropower should be able to provide short- to medium-term buffering of the enhanced variability and uncertainty wind power induces in the overall load net wind. Adding wind power to the system may or may not help hydropower meet power and other system demands, and the influence on other hydro functions, such as water deliveries, must be considered. That said, even within the constraints currently imposed on hydropower, it is a valuable system balancing resource, and possesses the inherent qualities needed to facilitate wind integration. Five of the case studies of Task 24 addressed hydropower impacts, the relevant conclusions of which are summarized below.

- Australian Case Studies #1 and #3: Hydro Tasmania's system was modeled with 1,850 MW of peak load; a 900-MW minimum load; 2,267 MW of hydropower, and 630-MW/480-MW export/import capability via a high-voltage direct current (HVDC) interconnect with the Australian mainland. The studies found that a high level of wind power can be integrated into the Tasmanian system, up to 1,300 MW, if the interconnect with the Australian mainland is used and if measures are taken to address low system inertia. The study also identified that commitment of additional hydro generators operating in either synchronous condenser mode or tail water depression mode can largely improve the integration of the wind generation in Tasmania and mitigate problems associated with low system inertia.
- Australian Case Study #2: With respect to reservoir storage, in the case of islanded operation of a Tasmanian power system, system storage is unable to effectively absorb all output from large-scale wind generation due to coincident of high winds and high inflows. There is an increasing negative impact on storage as wind generation capacity is increased. Interconnecting to the Australian mainland, via the addition of the high-capacity HVDC interconnection, significantly increases the ability to integrate wind generation in Tasmania without a negative effect on the energy in storage.
- Swedish Case Study #1: The first Swedish case study analyzed the possibility of balancing wind power with hydropower plants located along one certain river. The amount of wind power studied extrapolated to a penetration in whole Sweden equal to 6.5–7.5 TWh/year, or 5% of the total energy production per year. The results from the simulations indicate that Swedish wind power installations that generate about 2–2.5 TWh/year do not affect the efficiency of the Swedish hydro system. At wind power levels of about 4–5 TWh/year, it is estimated that the amount of installed wind power should be increased by about 1% to compensate for the decreased efficiency in the hydro system. At wind power levels of about 6.5–7.5 TWh/year, the additional wind power needed to compensate for loss of hydro efficiency is about 1.2%, but this figure has to be verified with more extended simulations.

- U.S. Case Study Grant County Public Utility District (PUD): This case study considered two hydropower plants located along the Columbia River and operated by the Grant County Public Utility District No. 2 (Grant PUD). The levels of wind penetration considered in were 12 MW (1.8%), 63.7 MW (7.8%), and 150 MW (18.6%), with each percentage computed as a percentage of peak load (including sales of energy). Study results for the 2006 data year suggest that the overall impact on system statistics for regulation and load following is quite modest, even at a wind energy penetration of 150 MW (~19% wind penetration by capacity). The small statistical impact suggests that, absent other constraints, the physical generation resources are sufficient to handle wind variability at this level. However, due to changes in the distribution of load following hourly changes, there are some potentially significant operational challenges in scheduling the resources without infringing upon system constraints. To address this, an hourly simulation was conducted using day-ahead wind power forecasts, revealing that additional instances of dipping into contingency reserves occur due to missed wind power forecasts, and that additional short duration excursions below the minimum flow requirements (for fish survival) also occur. The increases, however, are only modest and many can likely be handled during the day of operation, though at some cost.

Economics

The wind integration and hydro system impact studies have demonstrated the technical feasibility of integrating wind power and hydropower, even in systems with either transmission or hydropower constraints. Beyond the technical feasibility, two case studies investigated whether or not integrating wind was practical from an economic point of view, or looked at the effect of wind integration on the market. These two studies represent a valuable contribution to the Task, and are a good start in addressing the overall question of economic feasibility.

- Canadian Case Study: Natural Resources Canada conducted a study for a small public utility in the U.S. along the Columbia River that demonstrated that using wind power to address load growth is economically feasible. It was also shown that the hydropower resources available to the utility being studied were satisfactory to supply low-cost balancing resources. In practice, due to underproduction of the wind power plant, it was found that the wind power would not have been economically favorable without Renewable Energy Production Incentives.
- Finnish Case Study #2: The study analyzed wind power energy penetrations of 10%, 20%, and 30% in the Nordic system (74,000-MW peak load). Because old power plants were not retired in the study, there were no problems with system adequacy. Balancing this amount of wind power was shown to be feasible, but it was determined that a large penetration of wind power in a hydro-dominated power system will lower the spot price of electricity dramatically, which creates a challenge to get new investments in the system. It is unclear whether this kind of system could arise based on the markets even if it would be the most cost-effective way to serve load from a system perspective.

As the breadth of the case studies indicate, integrating wind and hydropower can be quite complex. A summary of some key observations and conclusions from the work and discussion among the participants are provided below.

- Figure 1 provides a conceptual view of a practical configuration for combining wind and hydropower in a balancing area. The key take-away from this illustration is that wind and hydropower are system resources that help serve the load via the transmission grid, and that they are each controlled by the transmission system operator (TSO). Addressing the incremental impacts of wind integration is done in the context of the entire system, with all of its load and generation resources, and not in isolation from them (i.e., not one wind power plant balanced by one hydro plant to produce a flat output).
- When addressing wind integration, one should consider the holistic impact of wind power on the system (e.g., a cost-benefit analysis directed toward the electricity customer and the effect on transmission system reliability), and not just the enhanced balancing requirements due to wind power's variability and uncertainty. For example, wind power will enhance balancing requirements and incur an "integration" cost; however, at the same time, the overall cost of electricity to the consumer may decrease due to wind energy displacing higher cost generation resources.
- The setup and operation of the transmission system and balancing area authority will have a profound impact on the ability to integrate wind power and the integration costs incurred. TSOs, where the timing of transactions (committing units, buying and selling of electricity, ancillary services, and reserves) is frequent, are more capable of integrating wind power and at lower costs.
- Transmission interconnections are important as they can limit wind and hydropower integration due to transmission constraints or congestion, or facilitate integration via power exchanges with neighboring systems. Larger balancing areas can more easily integrate wind and hydropower.
- Electrical systems can function within a liberalized electricity market, via a vertically integrated utility that participates with neighboring systems via bilateral transactions, or some combination of the two. Wind integration costs and impacts tend to be reduced in market systems, especially those with many market actors and flexible resources.
- The wind/hydro case study results were consistent with other wind integration studies in that the presence of an efficient and liquid electricity market has a large positive influence on the economics, frequently dominating all other factors. Furthermore, an important factor in interpreting the economic consequences of integrating wind and hydro is the perspective taken by the study: for the overall benefit of the electric customer vs. a single actor in the market (e.g., a utility or wind developer).
- In conducting wind integration studies, the modeling assumptions and techniques can have a significant influence on the results. Therefore, these should be well-specified and understood when interpreting results and comparing different studies. Wind integration studies often involve the use of production cost models that simulate hourly operation of the power system. General production cost models (those not specifically developed for or by a hydropower-dominant utility) need improvements in how they model hydropower operation, water balances, and constraints, in order to better investigate the nuances of wind and hydro

integration (e.g., the impact of enhanced system balancing requirements on hydro system constraints or the ability to model the constraints). Virtually all production cost models require further improvement in how they handle wind power and wind power forecasts.

- At low wind penetration levels (~1%), wind integration impacts and costs are minor. These transition to more cost and complexity as penetration levels increase to ~20%. Beyond ~20%, changes in system operational practices are likely necessary to optimally integrate wind and hydropower (e.g., use of advanced wind forecasting models incorporated into system planning). Islanded or small power systems with weak interconnections may more readily experience the effects of the enhanced variability in net load and increased reserve requirements caused by wind integration, including impacts on system inertia, and require attention in system planning.
- Non-power constraints on the hydropower system can influence the ability to integrate wind and hydropower. Such constraints may include higher priority functions of the hydro facility that dictate how water is run through the generators, such as irrigation water deliveries, environmental regulation (e.g. fish passage), recreation, or flood control. While these non-power constraints are important, they frequently occur on time scales of system operation different than those related to wind/hydro integration. Therefore, they do not tend to be prohibitive and often may not significantly influence the wind and hydro integration, although at times they do reduce hydro system flexibility. Of the Task 24 participants, these constraints only played a significant role in hydro systems in the United States.

In summary, while hydropower systems possess special characteristics and operating constraints, the inherent flexibility of their generators and the potential for energy storage in their reservoirs make them well suited to integrate wind into the power system. As wind penetration increases, the agile hydro generation can address wind integration impacts and this service represents an economic opportunity for many hydro generators.

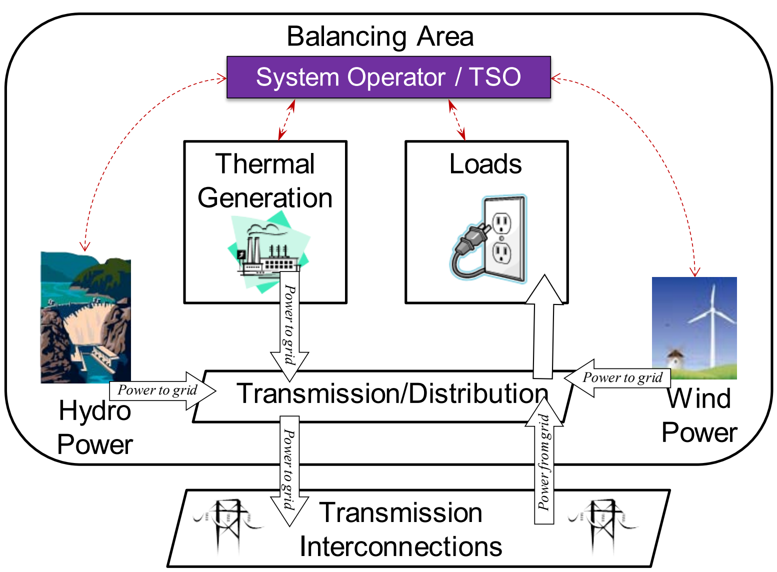


Figure 1. A practical configuration for wind and hydropower integration (Source: T. Acker presentation, Task 24 R&D Meeting #5, Québec City, Québec, Canada, June 2008)

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1 Background Information and Objectives of Task

Over the past several years, concern has increased regarding meeting the growing electrical demand while also protecting the environment. As a result, an emphasis on building new, clean, renewable energy resources has arisen, often manifested via politically mandated standards, a perceived need to cut carbon emissions, or the introduction of new, more cost-effective energy generation. Hydropower and wind power are examples of two renewable resources being called upon to meet the need for new generation, and they are also among the most affordable.

Worldwide, hydropower facilities represent a significant amount of installed electric generating capacity, responsible for 12.3% of electrical energy generation in 2007 (IEA 2008). IEA statistics indicate that at the end of 2000, there was in excess of 410,000 MW of installed hydropower capacity within IEA member countries, with about half in Europe and half in North America. Since then, hydropower generation has increased by more than 13,000 MW in IEA member countries (IEA 2008). Hydropower is typically one of the least expensive generation sources, often with generators that are outfitted with automatic generation controls (AGCs) that allow very rapid response to changes in electricity demand. Hydropower generators can supply valuable “ancillary services” required to maintain the instantaneous balance between generation and load. The ability of hydropower to provide these services, along with its low-cost energy and, in some cases, energy storage, make it one of the most flexible and valuable generation assets on the grid.

Over the past decade, electrical energy derived from utility-scale wind turbines (with capacity ratings greater than 1 MW per turbine) has become cost competitive relative to conventional electrical energy resources, especially natural-gas-based generation (see Figure 1). Furthermore, as wind turbine technology has developed, turbine reliability has become very high (with greater than 98% availability), and there is now significant experience in designing, financing, building, and operating large wind power plants. As a result, the installed capacity of wind power has increased dramatically during the last decade, from 15,400 MW in 2000 to in excess of 120,000 MW at the end of 2008 (IEA 2008, USDOE 2009). This significant growth is expected to continue over the next several years. In addition to its cost competitiveness, wind energy brings other benefits—it has long-term price stability, no emission of climate-change gases, requires no water, is an indigenous resource, and can foster rural economic development.

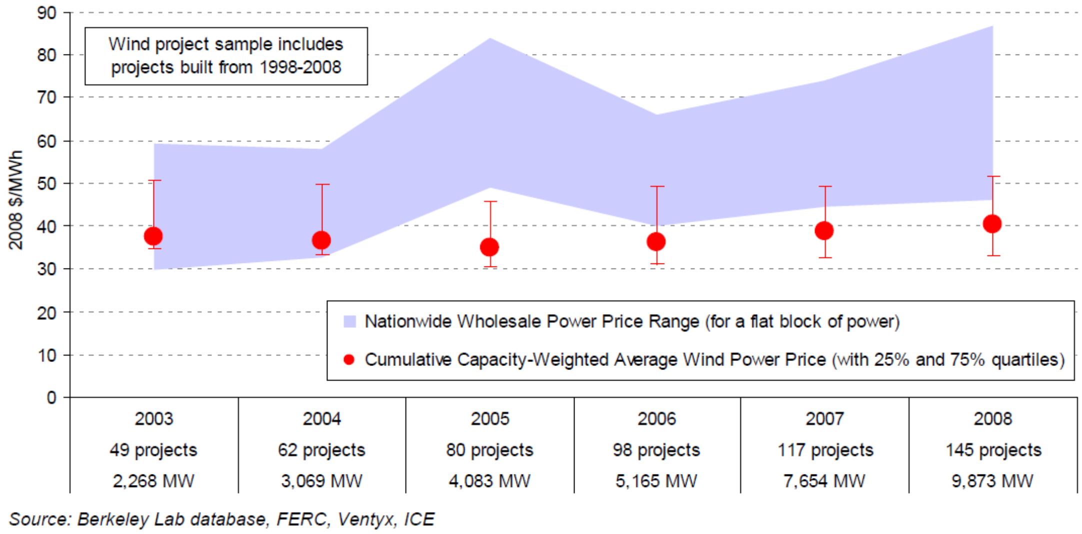

Figure 2. Average cumulative wind and wholesale power prices over the past 6 years in the United States (Source: Wiser and Bolinger 2009)

While wind energy has many positive aspects, it also has different generation characteristics than conventional utility resources. In particular, because meteorological processes drive wind, it is inherently variable. This variability occurs on all time frames of utility operation from real-time, minute-to-minute fluctuations through yearly variation affecting long-term planning. In addition to being variable, it is also a challenge to accurately predict wind energy production on the time scales of interest to utility planners and operators: day-ahead and long-term planning of system adequacy (i.e., meeting the system peak load during the year). Wind energy is more predictable in the hour-ahead time frame, but even then, the uncertainty in wind forecasts can be significant and must be accounted for in utility operation and dispatching.

In order to minimize impacts and maximize benefits, each utility or balancing area[2] (BA) that incorporates wind energy must learn how to accommodate its uncertainty and variability in operational and planning practices, and to do so while maintaining system reliability. A system that includes hydropower in its pool of generating resources may be well suited to accommodate wind energy due to hydropower's inherent flexibility. That said, hydropower also possesses different operating characteristics that warrant special consideration, as compared to flexible thermal generation resources (e.g., simple cycle gas turbines, combined cycle gas turbines). For example, run-of-the-river hydropower must be used or spilled[3] at times when the water is naturally flowing, limiting its flexibility. Alternatively, hydropower facilities with large reservoirs may allow considerable discretion in regard to when water is released, providing significant flexibility. On river systems with multiple hydropower facilities, water releases at an upstream dam will likely influence and constrain the water releases and power generation at the downstream dams. This interaction on a river system—especially for one in which multiple

[2] A balancing area here refers to be a subset of the broader interconnected transmission system for which a single transmission system operator or balancing area authority is responsible for maintaining grid safety and reliability standards.

[3] *Spill* refers to water that is passed through a hydropower facility but not used for power generation. Frequently this water passes over or through the *spillway* on a dam.

owners or operators are involved—may require joint planning and the development of complex operating practices that will permit some form of optimal, coordinated operation between the facilities, or at least fair operation.

Given the background and due to the potential for synergistic operation of wind and hydropower facilities within or across balancing areas, and because considering the unique operating constraints and complexities prevalent with hydropower, utilities and researchers from several countries expressed interest in investigating "wind and hydropower integration" through broad collaboration and information sharing. In November 2003, the IEA Wind Implementing Agreement (IA) convened Topical Expert Meeting #41 on the "Integration of Wind and Hydropower Systems" in Portland, Oregon, U.S.. As a result of this meeting, a proposal was introduced for IEA Wind to form an "Annex" or "Task" to foster international collaboration in studying the potential for integrating wind power in electrical systems with hydropower. In May of 2004, IEA Wind established R&D Task 24, "Integration of Wind and Hydropower Systems." The member countries, contracting parties, and participating organizations in the Task are listed in Table 3.

Integration of wind power into power systems is an active area of research. There are organizations devoted to its study (e.g., see www.uwig.com or www.windintegrationworkshop.org), and there have been numerous publications related to the topic including some produced by the IEA (e.g., IEA 2005, IEA 2008a, Holttinen et al. 2008). IEA Wind established another R&D work task in 2005, Task 25 on the "Design and Operation of Power Systems with Large Amounts of Wind Power," which deals specifically with issues related to wind integration impacts, costs, and analysis techniques. Tasks 24 and 25 bear many similarities centered on wind integration, but Task 24 focused on electrical systems with hydropower. The goal in conducting the collaboration established in Task 24 was to study wind integration in a variety of electrical system configurations (load, generation, and transmission); hydro system configurations and characteristics; and market and operational configurations—all of which is more than could be studied by any one country alone—and to understand the potential for and limiting factors in integrating wind into systems with hydropower.

The remaining sections of this chapter will describe aspects of electrical system planning and operation of relevance to wind integration; describe what is meant by wind and hydro integration in the context of this task; list the specific objectives of Task 24 along with the means to achieve these objectives; and provide an overview of the Task 24 final report, which is organized into two volumes.

Table 3. Task 24 member countries, contracting parties, and participants

Country	Contracting Party	Participant
Australia	Australia Wind Energy Association	Hydro Tasmania
Canada	Natural Resources Canada	Natural Resources Canada Manitoba Hydro Hydro Québec
Finland	TEKES National Technology Agency, Finland	VTT
Norway	Norwegian Water Resources and Energy Directorate	SINTEF Energy Research Statkraft Energy
Sweden	Swedish Energy Agency	KTH Swedish Institute of Technology
Switzerland	Swiss Federal Office of Energy	EW Ursern
United States	U.S. Department of Energy	National Renewable Energy Laboratory Grant County Public Utility District Sacramento Municipal Utility District Northern Arizona University

1.1 Electric Utilities and System Operation

The purpose of the information provided here is to provide a description of electrical system planning and operation that is generally applicable, but independent of any particular system. From this foundation, the specific issues of importance to wind integration in systems with hydropower will be highlighted, laying the foundation for the specific goals of Task 24.

1.1.1 Electric Utilities and Markets

Electrical power to homes, businesses, and industry is typically provided by an "electric utility." Electric utilities were typically established as vertically integrated, isolated systems, responsible for generation, transmission, and distribution of the electricity, often through a state-regulated monopoly. As time progressed and the transmission system expanded, creating stronger, high-voltage connections between the various utilities, cooperation among the utilities increased and eventually resulted in the formation of organizations that permit sharing of certain reliability requirements such as contingency reserves (e.g., power pools). Through cooperation, utilities could gain the benefits that result from aggregating load and resources. More recently, over the past two decades, operation of utility systems has been evolving into market-based systems with many independent organizations where significant amounts of energy are bought and sold over large, high-voltage, interconnected transmission systems. Both types of systems exist throughout IEA countries, including systems that are some combination of each. Examples of well-functioning energy markets are the "NordPool" in the Nordic countries; the Australian Energy Market Operator (AEMO, formerly the National Electricity Market) in Australia; and the Midwest System Independent Operator (MISO) in the Midwestern United States. An illustration of Regional Transmission Organizations (RTOs) in Canada and the United States where electricity markets are operated is provided in Figure 3. Vertically integrated utilities are also prevalent, although the transmission and generation arms of these utilities are now normally split into two separate but dependent companies. Examples include the Grant County Public Utility District (PUD) and the Arizona Public Service Company in the Western United States, and

Hydro Québec in the Québec Province of Canada. These utilities typically transact with other utilities or electric services providers via bilateral agreements, many of which are long-term, and in some cases through participation in neighboring market systems (e.g., Manitoba Hydro's participation in MISO). Regardless of the organizational and economic structure, the basic function is the same: the customers purchase electricity, and it is the responsibility of those entities involved in operating the electrical system to plan for and provide affordable and reliable electricity services. In all cases, a TSO or balancing area authority is responsible for balancing the instantaneous aggregation of customer requests for electricity (i.e., the load) with the available generation and transmission resources while maintaining the safety and reliability of the electrical grid. Generally, some type of regulatory body generally overlays the TSO/utility/electricity market—typically, this is done at the national level to create and implement the rules concerning safe, reliable, fair, and efficient operation of the electric system.

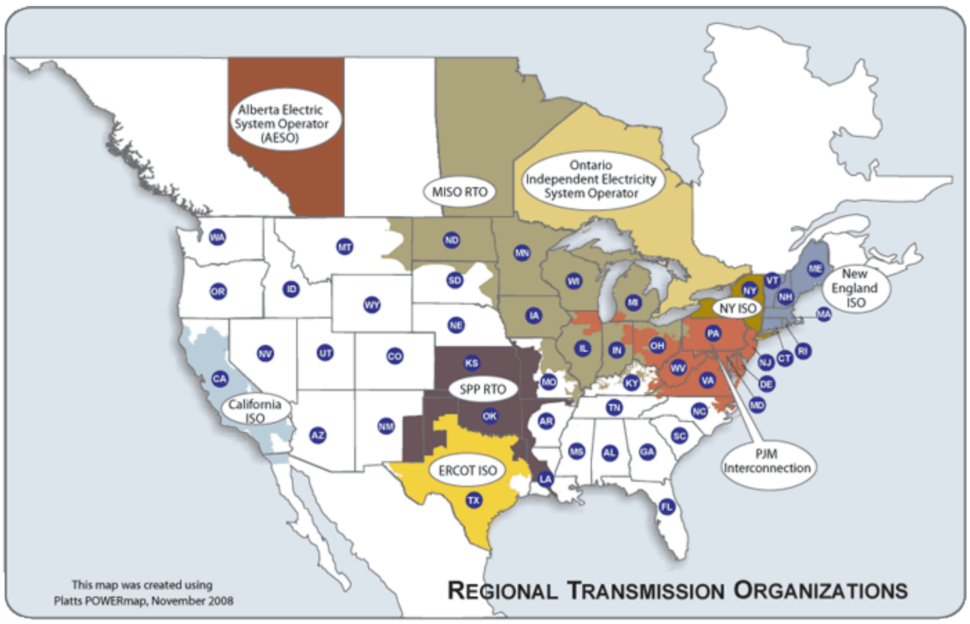

Figure 3. An illustration of the many regional transmission organizations that have arisen in Canada and the United States (Source: www.ferc.gov/industries/electric/indus-act/rto/rto-map.asp)

1.1.2 Ancillary Services for Power System Reliability, Security, and Power Quality

Electrical generation resources, to a large degree, are planned for well ahead of time: months to years based on the expected magnitude and temporal patterns of customer load. The load, though predictable and varying in expected ways, possesses an unpredictable component based on customer preferences and requirements; meteorological conditions (e.g., heating or cooling); market conditions; unforced outages of generators; etc. Therefore, TSOs have been built to accommodate the *uncertainty* and *variability* of load through use of "reserves" that are generally flexible generation resources that can ramp/start/stop quickly or through market or operational flexibilities (e.g., frequent scheduling intervals).

Interconnected power systems are large and extremely complex machines. The mechanisms responsible for their control must continually adjust the supply of electric energy to meet the combined and ever-changing electric demand of the system users. There are a host of constraints and objectives that govern how this is done. In total, however, those actions must result in the following:

- Keeping voltage at each node (a point where two or more system elements—lines, transformers, loads, generators, etc.—connect) of the system within prescribed limits
- Regulating the frequency (the steady electrical speed at which all generators in the system are rotating) of the system to keep all generating units in synchronism
- Maintaining the system in a state where it is able to withstand and recover from unplanned failures or losses of major elements

Ancillary services is the term generally used to describe the actions and functions related to the operation of a balancing area within an interconnected electric power system necessary for maintaining performance and reliability. While there is no universal agreement on the number or specific definition of these services or the names for them, the following list generally encompasses the range of technical aspects that must be considered for reliable operation of the system:

- *Regulation or Primary Reserve (Operational Reserve):* The process of maintaining system frequency by adjusting certain generating units in response to fast fluctuations in the total system load
- *Load Following or Secondary Reserve (Operational Reserve):* Ramping generation up (in the morning) or down (late in the day) in response to the daily load patterns
- *Frequency-Responding Spinning Reserve (Capacity/Contingency Reserve):* Maintaining an adequate supply of generating capacity (usually online, synchronized to the grid) that is able to quickly respond to the loss of a major transmission network element or another generating unit
- *Supplemental Reserve, 10-Minute Reserve, 30-Minute Reserve (Capacity/Contingency Reserve):* Managing an additional back-up supply of generating capacity that can be brought online relatively quickly to serve load in case of the unplanned loss of operating generation
- *Voltage Regulation and Volt-Amp-Reactive (VAR)*[4] *Dispatch:* Deploying devices capable of controlling reactive power to manage voltages at all points in the network.

In this list, the reserves denoted as *Operational Reserve* are expected to be used on a daily basis to cover the variability of the system load and errors in its prediction, while the *Capacity/Contingency* reserves are allocated to cover failures in the electrical system, such as loss of the single largest generating unit or transmission linkage.

[4] Electric machinery requires two components of current to operate: power-producing current and magnetizing current. Power-producing or working current is current that is converted by the equipment into work. The unit of measurement of active power is the Watt. Magnetizing current, also known as reactive current, is the current required to produce the flux necessary to the operation of electromagnetic devices. Without magnetizing current, energy could not flow through the core of a transformer or across the air gap of an induction motor. The unit of measurement of reactive power is the VAR. Management of reactive power is the primary mechanism for controlling voltage at points within the network. System operators dispatch various devices capable of producing reactive power, including generators, shunt capacitor banks, static VAR compensators, etc., to control voltages in response to continually varying customer demand.

Table 4 compares the terminology used in describing reserves/ancillary services in Australia, Canada, Germany, Ireland, the Nordic system, and the United States. These ancillary services are critical for maintaining the reliability and security of the electric grid. For any foreseeable combination of equipment failures or miss-operation, operating generating units must remain synchronized to prevent cascading equipment outages and subsequent blackouts. Figure 4 depicts a conceptual view of these ancillary services and their associated time frames, as relevant in North America. In this figure, *Scheduling* and *Unit Commitment* refer to the act of optimally planning generation resources and reserves ahead of the actual hour of operation, which must occur based on forecasted data on system load (as well as wind power, unit availability, hydropower, etc.).

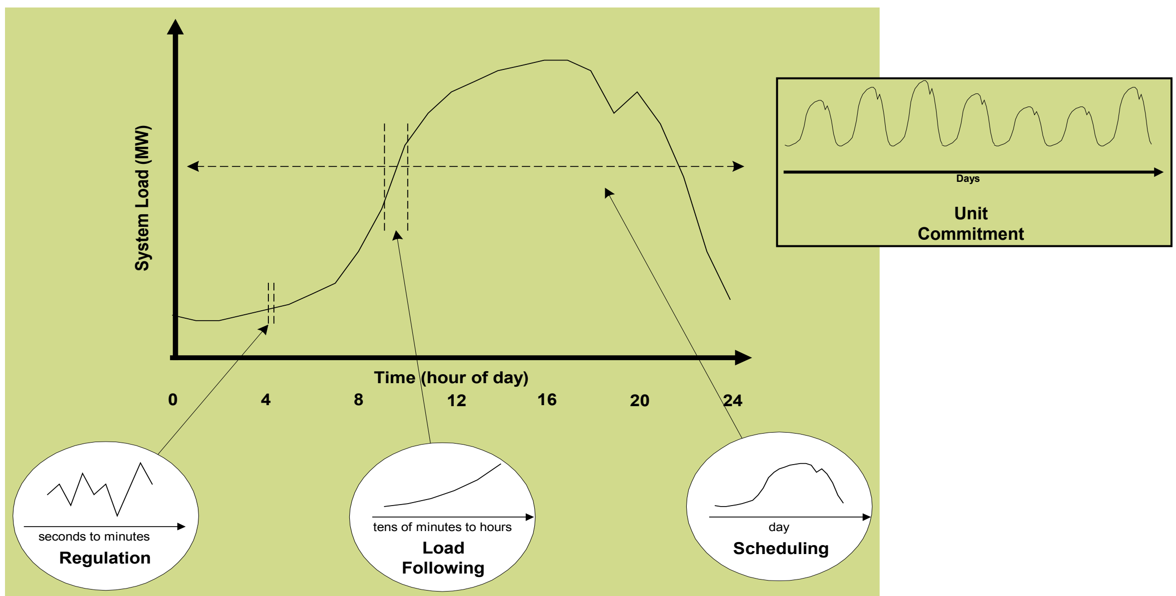

Figure 4. Time scales of importance when considering ancillary service impacts of integrating wind energy in the power system (Source: National Renewable Energy Laboratory)

Historically, a single entity had complete autonomy over operation of the generation and transmission assets in a service territory and the responsibility for operating them in a manner to achieve high reliability at the lowest cost. Ancillary services are tools for achieving these goals. With the deregulation of the wholesale electric power industry, the institutional responsibility for some of these functions has been reallocated to RTOs, TSOs, or other similar organizations. However, the technical reality has not changed in that these services must still be provided somehow, some way, by someone.

The implementation of competitive markets for ancillary services is in its relative infancy and is not uniform from country to country, or even within single countries. The emergence of market competition, in any form, has changed many of the procedures and processes for power system control and operation. Bidding supply into markets for the next hour or next day has replaced the historical top-down decision-making process used to commit and schedule generating units. Spot markets have supplanted some bi-lateral agreements between neighboring utilities for exchanging economic energy on short notices. In some locales, planning for the appropriate level of reserve supply is now the function of capacity markets.

1.1.3 How Ancillary Services are Provided

Meeting the operational objectives for the power system is accomplished through coordinated control of individual generators as well as the transmission network itself and associated auxiliary equipment such as shunt capacitor banks. How individual plants are deployed and scheduled is primarily a function of economics. Historically, vertically integrated electric utilities would schedule their generating assets to minimize their total production costs for the forecast load while observing any constraints on the operation of the generating units in their fleet. In bulk power markets, competitive bidding either partially or wholly supplants the top-down optimization performed by vertically integrated utilities. In either case, the economics of unit power production have the primary influence on how a plant is scheduled. In addition, the entity responsible for the operation of the balancing area—an individual utility, TSO, or RTO, for example—must manage some generating units to regulate frequency and control power exchanges in real time, to make up discrepancies between actual and forecast loads, and provide adequate reserves to cover an unexpected loss of supply.

Table 4. Types of operational reserves employed by TSOs in planning for balancing load and generation for three time scales of relevance (Source: adapted from IEA 2005)

	Fast Responding Reserve (seconds)	Medium-Term Reserve (intra-hour)		Long-Term Reserve (hours to days)
Australia	Contingency reserves (Frequency Control Ancillary Services[5]) Fast 6 seconds reserve for both raise and lower service; Also regulation FCAS service as part of AGC	Slow 60 seconds reserve for both raise and lower service	Contingency reserve; Delayed service available in 5 minutes	N/A
Canada: Québec	Regulation horizon: 1 minute with 1- to 5-seconds	(No specific reserve defined: Hydro-Québec's system is 95% hydropower, which easily provides load-following capacities)		Balancing reserve for load forecast and wind forecast uncertainties, and risk of outage: 1 to 48 hours
Germany	Primary reserve: available within 30 seconds, released by TSO	Secondary reserve: available within 5 minutes, released by TSO	Minute reserve: available within 15 minutes, called by TSO from supplier	N/A
Nordpool: Denmark, Finland, Norway, Sweden	Primary reserve: activated automatically by designated generators in every country		Nordic Regulating Power Market – bids activated in 10 minutes, from the country having cheapest bid in list	Some TSOs contract some capacity that can be activated during winter high load periods
Ireland	Primary operating reserve: available within 15 seconds (inertial response/ fast response)	Secondary operating reserve: operates over timeframe of 15–90 seconds	Tertiary response: from 90 seconds onwards (dynamic or static reserve)	N/A
United States	Regulation horizon: 1 minute to 1 hour with 1- to 5-second increments	Load-following horizons: 1 hour with 5- to 10-minute increments (intra-hour) and several hours (inter-hour)		Unit-commitment horizon: 1 day to 1 week with 1-hour time increments

The efficiency of thermal generating units typically varies with loading, so for each unit there is a point at which the cost of energy produced will be at a minimum. For large, fossil-fired and

[5] In Australia, all reserves are called Frequency Control Ancillary Services (FCAS). All FCAS services are commodities on the market subject to 5 minutes dispatch. After a contingency, all FCAS reserves need to be restored within half an hour.

nuclear generating units, the cost of generation generally declines with increasing loading up to rated output. As a result, the economics dictate that these units should be "base loaded" for as many hours as possible when in operation.[6] Other factors, such as thermal system time constants or mechanical and thermal stresses, may also result in certain units being loaded at fairly constant levels while online.

Against these operating constraints for certain units, other generating resources are deployed and scheduled to not only produce electric energy but also to provide the flexibility required by the operators to regulate system frequency, follow the aggregate system load as it trends up in the morning and down late in the day, and provide reserve capacity in the case of a generating unit or tie line failure. Some of these functions are under the auspices of a central, hierarchical control system generally referred to as the AGC. Others are the result of human intervention by the balancing area operators. In either case, the generating units participating in the system control activities must do the following:

- Be responsive to commands issued by the balancing area energy management system, otherwise known as "being on AGC"—participating in AGC generally requires a specific infrastructure for communications with the control center, the Supervisory Control and Data Acquisition system
- Operate such that there is the appropriate "head room" to increase generation or "foot room" to reduce generation without violating minimum loading limits if commanded by the system operator or energy management system
- Be able to change output (move up or down, or "ramp") quickly enough to provide the required system regulation or load following

As the electric power industry evolves, it is increasingly likely that third-party generators will play a large role in balancing area operations through various mechanisms and markets for ancillary services. One such mechanism is the short-term imbalance market, sometimes conducted on an interval as short as 5 minutes, during which generators bid to help the control area operators make up for real-time mismatches between control area supply and demand. In lieu of an imbalance market, utilities must arrange ahead of the hour for adequate short-term reserves to be online and available during the hour of operation.

1.1.4 Time Frames of System Planning

Within the year of operation, power system planning and operation occurs in two general time frames: planning up to the hour of operation and real-time operations within the hour. Some accounting then occurs after the hour of operation to rectify the system plan with actual operation. The up-to-the-hour planning is often divided into "day-ahead" and "hour-ahead" planning. For day-ahead planning, system operators or load-serving entities perform an economic optimization to commit units or secure energy via the market in an effort to minimize operating costs. This commitment process is based on load estimates for the following day. To the extent that the load estimates will be inaccurate, typically within 1% to 2%, additional and

[6]The term *base loaded* is generally used to describe the operation of large generating units with high capital and operating costs but low fuel costs that are loaded to near maximum capability for most of the hours they are in service. In traditional electric utility system planning, the base load is sometimes defined as the minimum hourly system demand over the course of a year.

unnecessary generation and reserves will be procured, leading to a sub-optimal commitment of units (e.g., generators running off their peak efficiency points, unnecessarily started) and increased operation costs. Units are frequently rescheduled and recommitted as the operating hour approaches and as load estimates become more accurate. However, even at the hour-ahead time frame, there is still load uncertainty and therefore sub-optimal commitment. The costs that are incurred in system operation resulting from uncertainty in forecasting and the resulting sub-optimal commitment are sometimes referred to as *unit commitment* costs.

The exact timing and mechanism in which generation units are committed differs from one balancing area to another, and depends on whether or not markets exist for trading power and ancillary services. Figure 5 shows a timeline of actions in Grant County PUD's generation planning activities. As illustrated, the plan for Day 3 is set on Day 1, but can be modified on Day 2 up to 18 hours before the beginning of Day 3. After this point, any further transactions typically occur during the day of operation as an hour-ahead transaction. In understanding the timing of transactions for Grant PUD, it is important to recognize that Grant County PUD is a relatively small utility (with less than 1,000 MW of peak load) and that it functions most similar to a vertically integrated utility with purchases and sales occurring through bilateral transactions. Another timeline for planning actions is shown in Figure 6 for the Nordel market. In this system, the spot market closes 12 hours before the day of operation. The Elbas market is an intra-day market to cover anticipated imbalances between the load and generation, and transactions on this market can be made up until 1 hour before the delivery hour. In both the Nordel market and the trading system in which Grant County PUD operates, there is no real intra-hour market, and the TSOs must plan for and acquire sufficient reserves an hour ahead for the hour of operation.

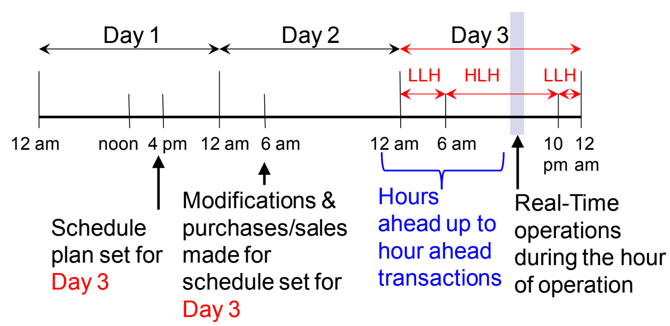

Figure 5. Typical time frame for planning operations at the Grant County PUD in the United States (Source: adapted from Acker et al. 2007)

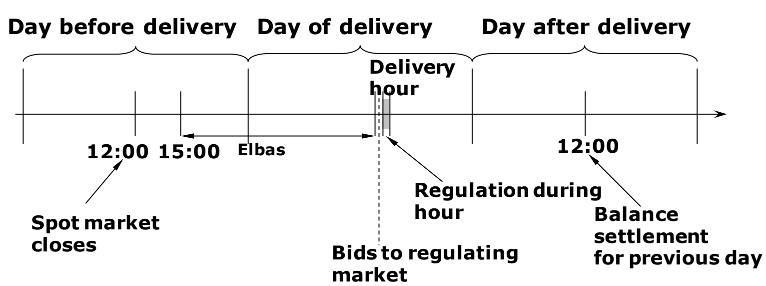

Figure 6. Timeline for day ahead, hour(s) ahead, and real-time planning operations for the Nordel system (Source: M. Olsson presentation, Task 24 R&D Meeting #2, Launceston, Tasmania 2006)

1.1.5 System Resource Adequacy

Beyond the reserves employed within the weekly time frame, utilities also engage in long-term capacity planning to ensure system resource adequacy. This level of planning is focused on guaranteeing sufficient generation is available to meet anticipated load in future years, especially the load during peak hours and months. The contribution of wind energy toward system planning is carried out using the standard methods that apply to any generator; for example, employing the loss of load probability for a generator or wind power plant and computing its effective load carrying capacity (ELCC) (see Milligan and Porter [2008]). To determine an accurate number for the ELCC, multiple years of data is desirable. A similar calculation is made for hydropower, and is dependent on the expected precipitation levels combined with existing hydrological and reservoir information, and generally changes from year to year. The amount of capacity that a given wind power plant can provide is often referred to as its *capacity credit* or *capacity value*, typically stated as a percentage of its nameplate capacity.

1.2 What is "Wind and Hydropower Integration"?

For the purpose of this research task, wind and hydropower integration refers to the study of wind integration into systems with hydropower, or more specifically, conventional hydropower plants (versus pumped hydropower). Wind and hydropower are both variable and uncertain over time frames of relevance for system planners: wind power varies within minutes and across seasons but is reasonably stable from year-to-year; whereas hydropower is typically highly predictable in time frames less than a couple of months to a year, but varies more from year-to-year as precipitation levels changes. As a mature technology, planning for long-term variations in hydropower is a common part of utility planning. Wind power, however, exhibits variations significant on the shorter timescales of utility operation and is commonly treated as a negative load in the system.[7] As will be explained later in this report, wind power will increase the overall variability and uncertainty that must be dealt with in a balancing area, thus increasing the system-wide need for reserves and ancillary services that were described earlier. This is especially true as wind penetration[8] climbs to appreciable levels (e.g., 5% to 10%; see IEA 2005). With respect to hydropower flexibility, there are essentially three different configurations:

- Run-of-river with very little water storage for which power generation is directly related to the natural inflow. With meteorological prediction, natural inflow forecast is normally used to predict the output, although there typically is still a low level of control up to a few hours depending of the capacity of the reservoir.
- Hydropower plants with reservoirs in two configurations:
    - Run-of-river type power plants with some storage, but in a cascade with one large reservoir upstream. In this case, with an upstream outflow prescribed, there is a relatively low level of flexibility at the power plant (perhaps a few hours to tens of hours)
    - A cascade of large reservoirs and power plants with more flexibility where power output is completely independent of the natural inflow pattern.

[7] A more in-depth discussion of the treatment of wind power as negative load is provided in Volume 2, Chapter 1.
[8] *Wind penetration* is defined here as the installed capacity of wind power divided by the annual peak system load. Other relevant methods of defining the wind penetration are presented and discussed in Volume 2, Chapter 1 of the Task 24 Final Report.

These three configurations have different levels of flexibility, and all have some flexibility to control their power output. In any case, due to its short-term flexibility and rapidly responding generators, hydropower can help address the challenges created by wind power through provision of ancillary services or via energy storage, and in doing so may benefit economically through a high-value use of its resource.

Since the introduction of wind power in a BA will increase the need for ancillary services, it will potentially change production patterns at hydropower facilities that either choose to provide these services or are required to do so. Due to differences in hydro systems, it is not obvious that deploying hydropower flexibility to accommodate enhanced ancillary service requirements will necessarily result in increased revenues for the hydropower operators or decreased system operating costs, though it certainly can. Moreover, due to the wide variety of balancing areas authorities or TSOs, electric markets or lack thereof, system load, generation and wind power characteristics, and the variation in hydropower systems themselves, it is not clear the extent to which wind power and hydropower can complement one another in any given BA, nor is it clear whether or not the experiences of wind and hydropower integration in one BA will apply to another. For example, a BA in need of new generation can benefit by building new wind power resources. Effectively using the hydropower resources available in this BA to help manage the enhanced variability and uncertainty introduced by wind power may lead to a low-cost, low-carbon solution for generation expansion. Alternatively, if wind power is required via political mandate in a BA where no new generation resources are required to cover load growth or for export opportunities, then wind power may not lead to decreased system operating costs (perhaps as would be the case for any new generation that is not required for meeting load). Furthermore, hydropower systems such as those in the United States often serve many purposes in addition to providing electrical power, some of which have a higher priority than power generation. Understanding how wind will impact other hydro operations and priorities that may exist, such as compliance with environmental regulations, irrigation water deliveries, flood control, etc., is important for TSOs and system operators that plan to incorporate wind power.

To summarize, this study of wind and hydropower is focused on wind integration into power systems with hydropower. While there are numerous issues to address in this study, they are all related to answering the following basic questions:

- *Grid Integration Impacts and Costs*: What is the impact of wind power on the power system balancing area, and specifically, the ancillary services/reserves required; long-term system planning (capacity value); and transmission system (e.g., scheduling bottlenecks)? What are the appropriate study methods?
- *Hydropower Impacts*: What impact will provision of these ancillary services have on the hydropower system? Impacts include those on the physical resources (e.g., operations and maintenance); operational flexibility; and hydro system priorities (e.g., meeting flow constraints, satisfying environmental regulations).
- *Economics*: What is the overall economic value of wind energy in the hydro system? What "opportunity costs" are incurred for the hydro system in providing ancillary services to wind power (thus not being available for scheduling), and what are the economic benefits/opportunities in doing so? What is the effect of market configurations and system

operation (e.g., scheduling intervals)? Are there wind/hydro "products" that can be of value both to power customers and hydropower providers (e.g., energy storage and redelivery)?

- *System Configuration*: Based upon the answers to the questions above, what are practical configurations for integrating wind and hydropower?

Building upon these basic questions, Section 1.3 addresses the specific objectives of Task 24 along with the means to achieve those objectives.

1.3 Task 24 Objectives and Means to Achieve

The primary purposes of Task 24 are to conduct cooperative research concerning the generation, transmission, and economics of integrating wind and hydropower systems, and to provide a forum for information exchange. Task 24's specific objectives are a follows:

- Establish an international forum for exchange of knowledge, ideas, and experiences related to the integration of wind and hydropower technologies within electricity supply systems.
- As it pertains to wind and hydropower integration, share information among participating members concerning grid integration, transmission issues, hydrological and hydropower impacts, markets and economics, and simplified modeling techniques.
- Through information sharing and exchange of ideas, identify technically and economically feasible system configurations for integrating wind and hydropower, including the effects of market structure on wind-hydro system economics with the intention of identifying the most effective market structures.
- Document case studies pertaining to wind and hydropower integration, and create an online library of reports.

To achieve these objectives, Task 24 relies on the research efforts within member countries related to integration of wind power and hydropower resources within an electricity supply system. An initial kick-off meeting was held in February 2005 to discuss the research and case studies to be undertaken, their related task objectives, and a consistent framework for problem formulation and results presentation. Five R&D meetings were held over the next 3 years following this initial meeting. The case studies conducted by the country participants were organized into three primary contexts: grid integration, hydro system impacts, and the electricity market and economics. The means to achieve the objectives was through the case studies listed in Section 1.3.1 to 1.3.4.

1.3.1 Grid Integration Case Studies

When considering wind power and hydropower integration, the first context to consider is that of the electrical transmission grid, whether that be an isolated grid serving an island community or a geographically large grid that spans a significant fraction of a continent. A large transmission grid is typically broken into several smaller transmission balancing areas in which reliability requirements are met while balancing loads with generation. Within any given balancing area, there may be several different types of generators, including natural gas turbines, coal-fired steam plants, nuclear power, hydropower, wind energy, and perhaps others. The average load within a control area typically varies in predictable daily and seasonal patterns, but also contains an unpredictable component due to random load variations (due to customers randomly starting and stopping electrical loads) as well as unforeseen events. As described previously, in order to compensate for these variations and unforeseen events, steps are taken to ensure system reliability by having additional generation capacity online to provide regulation (for the random load fluctuations) or set aside as reserves (to account for load forecast errors, unforeseen events, and unplanned outages)—in other words, through the provision of ancillary services. The generators within an electrical system each have their own operating characteristics. Some generators, such as coal-fired plants, primarily provide for base load and serve the slower daily variations in load. These generators are relatively slow to respond to load changes and have extended start-up and shut-down periods. Other generators, such as combustion turbines or hydro generators, are quick to respond to fluctuations, and can be started quickly. These more agile generators are the type used to provide regulation and load following on an hourly basis. The ability to provide ancillary services is of economic value to a generator above and beyond the energy produced while operating.

Introducing wind generation into a control area can increase the regulation burden and the need for reserves, due to its natural variability. However, since the control area has a constantly varying load, the impact of the wind plant variability imposed on the load variability may range from negligible to significant depending on the level of penetration and variability of the wind resource. Therefore, in order to accurately determine the impact on the control area reliability and the consequential incremental increase in need for ancillary services, the wind generation must be analyzed in the context of the transmission grid, fully encumbered with all of its loads, generators, and their corresponding characteristics.

Determination of the ancillary services imposed by wind integration on a grid is the first important step in understanding the potential for integration with hydropower resources. Hydropower, being a responsive generation resource capable of providing ancillary services, can supply the incremental increase in ancillary services caused by wind energy. The natural second step in the process of studying wind/hydro integration is to determine the extent of the ancillary services that can be supplied by hydro generation located in the balancing area or elsewhere within the interconnected grid. Given the existence of a finite amount of hydro generation on any given grid, only a finite amount of wind-energy-induced variability and uncertainty can be supported by the hydro. However, since system balance and reliability must be maintained within a balancing area, it is not necessary that wind and hydro resources be co-located, but rather, they may be located at their optimal locations, geographically far apart from one another. Furthermore, to the extent that electrical energy and ancillary services can be transferred from one balancing area to another, the potential for integrating wind with hydro resources is only limited by the transmission capacity within an interconnected grid. The resources themselves may be located great distances apart as long as they are electrically interconnected. Diverse geographical distribution of wind within a control area can have advantages in smoothing the wind variability and increasing the amount that can be effectively integrated with hydropower.

A unique advantage of hydropower compared to other generation resources, beyond simply providing ancillary services, is the ability to access the built-in energy storage capabilities of water within hydro reservoirs. Combining the energy storage ability of a hydro reservoir with wind energy could be synergistic and increase the value of wind and hydropower in the energy supply system. Hydropower generators could benefit by providing wind generators ancillary services and energy storage, meanwhile facilitating integration of wind energy on the grid.

Access to transmission is another very important consideration in developing wind energy. Many existing transmission facilities have been built for existing hydro or thermal resources, and there is little or no firm transmission capacity available. This limitation, however, is frequently contractual and not physical. In other words, there may be ample non-firm transmission capacity available for wind energy that is either inaccessible or too costly. Furthermore, to the extent that wind plants can be located near hydropower transmission facilities, there is potential to more fully utilize the existing transmission facilities (since many hydro facilities have capacity factors significantly less that 100%).

Given the wide variety of hydropower installations, reservoirs, operating constraints, and hydrologic conditions, there are many possible wind/hydro integration combinations and many possible solutions. Hydro generators typically have very quick start-up and response times and flexibility in water release timing, and therefore may be ideal for balancing the increase in variations induced by wind power within the context of the balancing area load. Studying grid integration of wind energy with hydropower lies at the heart of understanding its potential. Some desired outcomes of the grid integration case studies include the following:

- Identifying feasible wind/hydro system configurations; that is, investigating specific configurations with varying wind and hydropower characteristics, market arrangements, hydro constraints, balancing area characteristics, etc., and determining which are most practical and if some are not
- Identifying and developing techniques to analyze grid integration of wind energy, especially as they pertain to grids that include hydropower
- Understanding the capacity of wind energy that can be supported by hydropower in terms of the ancillary services
- Understanding the potential for energy storage
- Understanding the technical constraints and limiting parameters in wind power and hydropower integration

1.3.2 Hydro System Impact Case Studies

The second context within which to consider wind power and hydropower integration relates to the impacts on hydro system operation and, in particular, the non-hydropower functions. Depending on the relative grid integration impacts of the wind power, integration may necessitate changes in the way hydropower facilities operate. These changes may impact operation, maintenance, revenue, water storage, and the ability of the hydro facility to meet its primary purposes. Additionally, there may be positive hydro system benefits derived from integrating with wind, such as those related to water storage and compliance to environmental regulations. Without a proper understanding of these and other impacts and benefits, hydro facility operators may be slow to embrace the opportunities found in integrating with wind power. Therefore, study of the impacts on hydropower facilities and hydrological operations directed at determining benefits, detriments, and costs will be fundamental in paving the way for implementation of wind/hydro projects.

1.3.3 Market and Economic Case Studies

While grid integration and hydro system impact studies may demonstrate the technical feasibility to integrate wind power and hydropower systems, practical implementation will depend on the economic feasibility of a given project. This in turn will depend on the organization and characteristics of the electric power system, the load being served, interconnections with neighboring systems, and the type of electricity market in which the wind-hydro integration project is considered. Thus, the third context within which to consider wind/hydro integration is market and economics. Addressing economic feasibility in the context of the electric market characteristics will provide insight into which market types wind/hydro integration will be practical, as well as the key factors driving the economics. Additionally, to the extent that the organizational rules regarding scheduling and pricing of electricity are not constrained by physical generation and transmission facilities, there is opportunity to devise new methods of scheduling and pricing that will be advantageous to wind/hydro integration and permit better use of system resources. These case studies will address the effects of market structure on wind/hydro system economics with intent to identify the most effective market structures.

1.3.4 Simplified Modeling of Wind-Hydro Integration Potential

Based on characteristics of the local transmission balancing area loads, hydropower facilities, and wind power resource, simplified methods for approximating the amount of wind power that can be physically or economically integrated with existing hydropower should be devised. The analysis methods should include only the most influential hydro operational constraints and electric reliability concerns. The goal of this modeling objective is to provide a realistic technique for approximation of the potential magnitude for integrating wind power and hydropower, without the necessity of conducting an in-depth study. Simplified methods must still consider a “system-wide” perspective, with the understanding that wind power and hydropower interact within a larger grid that includes other generation resources. Because of this, it may be more fruitful for some investigators to consider simplified methods that study how much wind can be integrated in a large interconnected grid that includes significant hydropower resources, but not to consider specific hydropower resources.

1.3.5 Results Expected

Because the collective research of Task 24 relied on existing efforts within the member countries, all members did not address all case study contexts mentioned above.[9] However, one of the task objectives was information exchange among collaborators so that every participant had the opportunity to evaluate and comment on all case studies, including problem formulation and assumptions, analysis techniques, and results. This interaction is a key benefit of the IEA R&D tasks and fosters a collaborative environment that permits the substantial research capabilities in each country to more thoroughly address important and broad topics, beyond what they could do themselves. A complete list of the results expected upon formation of the task is presented below[10]:

[9] See Chapter 1 of Volume 2 for a table summarizing the research efforts and case study topics addressed by each member country.
[10] This list been taken directly from Article 4 of the Task 24 proposal “Results Expected.”

- Establish the technical and economic feasibility of integrating wind and hydropower systems in specific case studies that provide required power quality and dependability, and meet market criteria.
- Identify practical wind/hydro system configurations.
- Formulate a consistent method of studying and comparing the technical and economic feasibility of integrating wind power and hydropower systems.
- Determine the ancillary services required by wind energy, and the electric system reliability impacts of incorporating various levels of wind energy into utility grids that include hydro generation, including investigating the range of values for hydropower energy storage and other ancillary services, based on market opportunities and costs of wind integration, and including direct costs to the hydropower assets.
- Establish an understanding of the issues, costs, benefits, challenges, and opportunities directly related to integrating wind power and hydropower systems and the best ways to manage them.
- Develop guidelines for evaluating and comparing environmental and social impacts from hydropower, wind power, and transmission/distribution assets and systems.
- Investigate enhancing the flexibility of power planning through simulation of reservoir operation, selecting optimum configurations for specific sites and wind/hydrologic forecasting.
- Create a database of reports describing case studies and wind/hydro system analyses conducted through cooperative research of Task 24.

1.4 Report Organization

This final report of Task 24 has been organized into two volumes. The first volume provides the background necessary to understand the work undertaken by the task and the main results. The second volume focuses on the study methods employed and provides a thorough description of the case study projects and the results from each that are of relevance to the task.

The purpose of this introductory chapter was to provide the background necessary to understand the reasons for forming Task 24 and to present the member countries and organizations. The salient aspects of electrical system operation and planning were then described in order to lay the foundation upon which the results of the task are based. With this information in place, the meaning of “wind and hydropower integration” was defined followed by the objectives of the task and the means of achieving them. Chapters 2 and 3 provide an overview of wind power and hydropower, respectively, discussing the aspects of importance to Task 24 objectives and expected results. Chapter 4 describes power system operation and balancing in systems with wind power and hydropower, drawing upon the case studies and other relevant literature. Conclusions of the task and suggested future directions for the study are addressed in Chapter 5.

2 Wind Energy Overview

As the amount of wind power on the grid has grown to substantial amounts, large wind power plants have arisen ranging in size from 50 MW to on the order of several hundred megawatts. While less than 50 MW of smaller wind power installations may feed into the utility distribution system, large wind power plants often feed into a high-voltage transmission system through a substation, and in this sense look like a typical interconnected power plant. Modern wind turbines now function more like mature power generation technologies: they are able to adhere to low-voltage ride-through standards and provide reactive power support, and models for wind power plant behavior have been developed for transmission system electrical power system simulations. However, one of the ways in which wind energy does not behave like a traditional power generation resource is that it is not dispatchable (except for possibly shutting down operating turbines to shed generation), and there is significant uncertainty in its prediction.

Electric energy production from a large wind generation facility over a period of time—months, years, or the life of the project—can be estimated accurately enough to secure financing for the large amount of capital necessary to construct the facility. Over shorter time frames, however, production is less predictable. One of the most significant barriers to further development of wind generation stems from the fact that the processes and procedures for the design, planning, and operating of large interconnected utility systems are necessarily biased toward resource capacity (the rate of energy transfer to the grid, not the amount delivered over a longer period of time) to ensure the adequacy, reliability, and security of the electric supply for all end-users. Integrating large amounts of wind energy into the larger portfolio of electric generation resources requires some special considerations on the part of those charged with operating the electric system. Substantial amounts of wind generation in a utility system will increase the demand for the various ancillary services described in the previous chapter. The ability of and cost to the balancing area to provide the required level of these services for successful integration depends on the makeup of its generating fleet, agreements with neighboring balancing areas, and the existence of competitive markets for such services.

Chapter 4 of this report will address the impacts and costs of wind integration as investigated in the case studies performed for Task 24. The purpose of this chapter is to describe the salient aspects of wind energy relative to electrical system planning and operation, and in particular will describe the "value" of wind energy and the characteristics of wind power's variability and uncertainty in its prediction.

2.1 The Value of Wind Energy

An overall perspective on the value of incorporating wind energy into a utility system is shown in Figure 7. The green bar shown represents the cumulative positive financial benefits of wind energy accrued over the course of a year, typically normalized per megawatt-hour of wind energy production, the largest component of which is the marginal value of the wind energy. This marginal value is dependent upon *when* the wind blows and is higher during peak load hours and lower off-peak. It is also dependent on the market conditions, if that is relevant for a given utility (i.e., the utility participates in a market). Wind power also possesses a capacity value, as suggested in the figure. Although wind is primarily an energy resource, it will contribute some capacity toward the total system capacity required to meet peak system loads, and therefore avert the need for other capacity additions to the system. The amount of capacity value attributable to wind power is addressed later in this chapter. Wind power may also be attributed tax credits, such as is the case in the United States, or other credits or feed-in tariffs that add to its value. For example, in countries where emissions are limited due to environmental standards and there is a tax or fee associated with carbon (or other) emissions, a value can be calculated for the savings in emissions that would otherwise have occurred without wind generation. It is possible there will be other credits associated with wind energy as represented on the bottom of the green bar in the figure. For example, one might consider the hedge value of wind energy in mitigating fuel costs risks and reducing fuel costs associated with natural gas purchases and associate a value to it, see Bolinger et al. (2002). On the cost side, represented by the red bar, the three main costs identified are the cost of wind power, the transmission costs, and the "integration costs." Here, the dominant cost is the cost of wind power, and it is determined either by the annualized capital cost plus operations and maintenance (O&M), or it may be the contract price paid for the wind energy via a power purchase agreement, etc. The transmission costs are those costs associated with either upgrading the transmission system or building new transmission in order to bring the wind power to the grid. This leaves the integration costs, which are all those costs incurred in operating the system to accommodate the incremental variability and uncertainty that the wind power introduces into the system net load, above that associated with load alone. These additional costs are typically incurred as additional ancillary services and reserves, and should be inclusive of increased O&M costs due to more start-ups and cycling of existing units. For some systems, those including hydropower in particular, there may be an opportunity cost associated with diverting hydro resources from their normal economic use to provision of ancillary services. In the context of a wind integration study where a cost production simulation is run (see Volume 2, Chapter 1), this cost should be captured and included as either an integration cost or simply in assessing the overall cost of operation. Overall, there is generally a net benefit due to wind energy for a wide range of wind penetration levels, represented by the blue "net benefit or cost" bar in Figure 7, the magnitude of which varies from system to system based upon each system's conventional generation resources, load, wind resources, operational rules and constraints, and the market within which it operates. The "other benefits" shown correspond to non-monetized benefits, as might be the case for avoided carbon emissions, the hedge value of wind, etc.

Denny et al. (2006) present a good example of an analysis that considers the value of wind energy in the Irish power system. Another example wind integration study that considers the overall benefit of wind in a utility system is the study conducted by General Electric for the New York State Energy Research and Development Authority (GE Energy 2005).

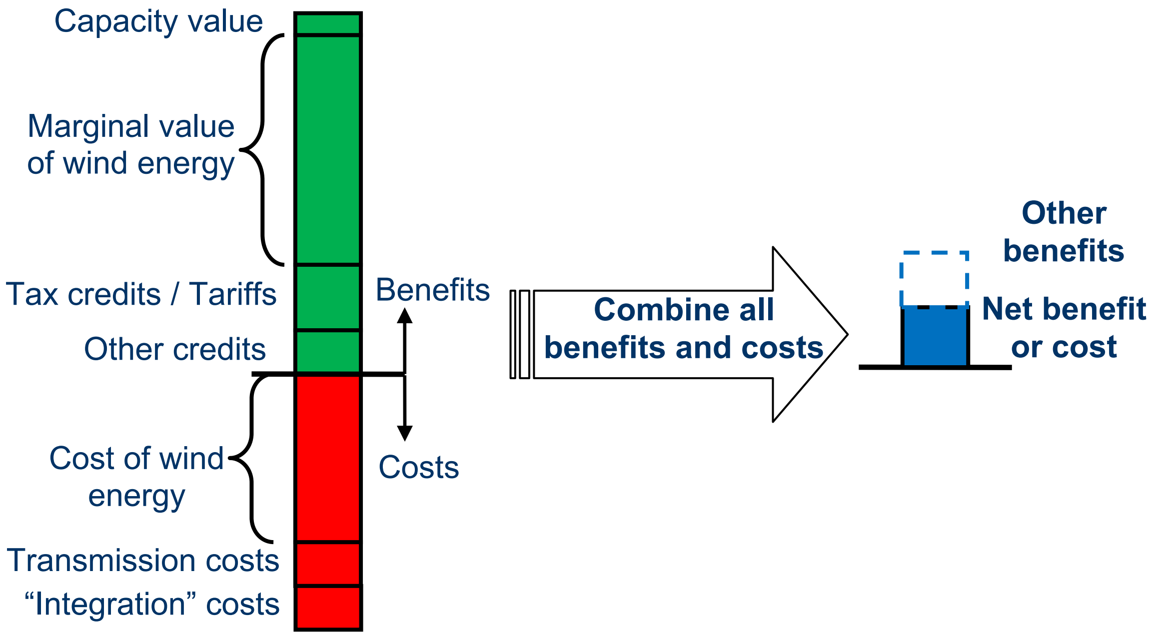

Figure 7. Overall perspective of the value derived from integrating wind into a utility system (Source: Acker 2007a)

2.2 Characteristics of Wind Power Variability

The characteristics of wind variability cross several time frames of power system operation and planning, from short, minute-to-minute fluctuation to longer-term seasonal and annual variations. One of the key challenges in large-scale wind integration is the lack of familiarity that system operators have regarding the magnitude and frequency of wind power output variations, and the impact that will have on system operation. Because these variations affect wind and hydropower integration, a summary of actual wind power variations will be provided here. The bulk of what will be presented draws upon the work of Wan at NREL, based on wind power output data taken from up to 35 wind power plants spread across the United States (Wan 2004, Wan 2005, Wan 2008).

2.2.1 Variability in the 1-Minute Time Frame

Because the 1-second changes in power output at a wind power plant tend to be quite small (<0.1% of installed capacity) and are uncorrelated between different power plants and even different turbines within a power plant (Wan 2004), the first time scale of significance to wind-hydropower integration is the 1-minute time frame. Variations of this resolution can impact the regulation required in operating the system. Figure 8 shows a distribution of 1-minute step changes (i.e., the difference in output from one minute to the next) at a 103.5-MW wind power plant over the course of 1 month. At this plant, 90% of the step changes were within 1% of installed capacity. The ramp rates shown are computed by dividing magnitude of change during a ramp by its duration, normalized by the wind power plant capacity. As a consequence, there are fewer ramps than step changes, and their magnitudes are smaller. This type of 1-minute variability is typical of a single wind power plant.

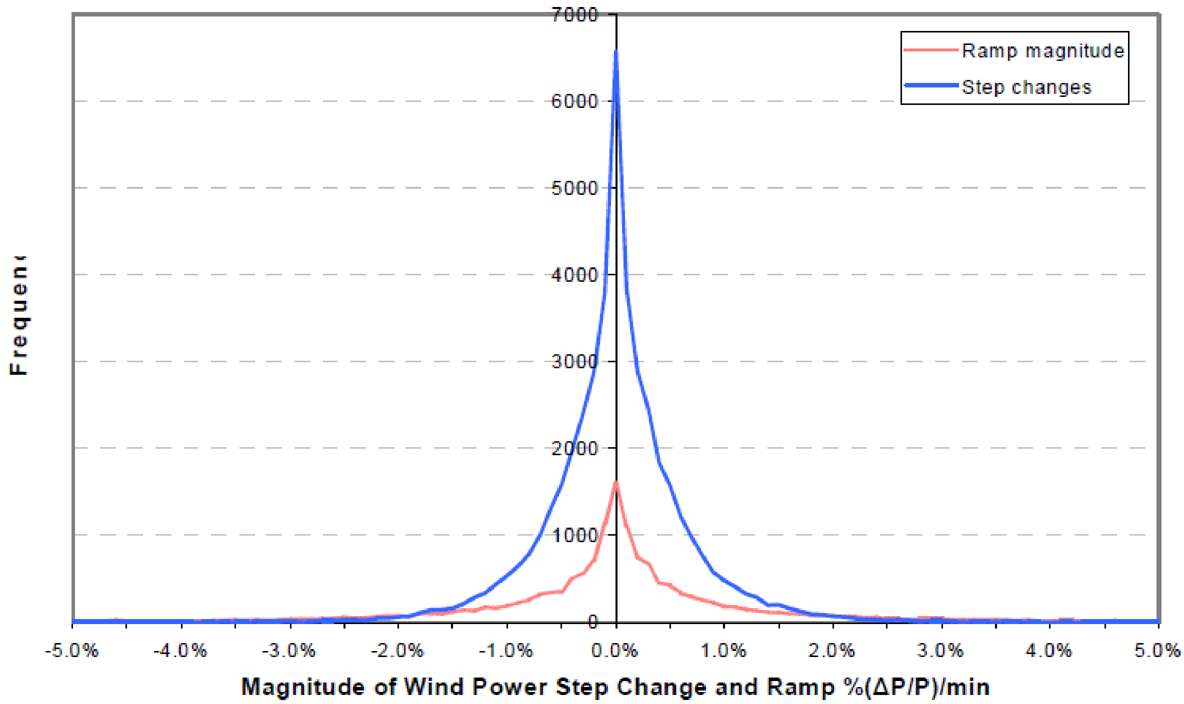

Figure 8. Distribution of 1-minute step changes and ramp rates based upon 1-minute data for a 103.5-MW wind power plant in Southwest Minnesota, U.S. (Source: Wan 2004)

Table 5 shows a statistical summary of the magnitude of 1-minute step changes at the same power plant depicted in Figure 8, but for 12 months of operation. As shown, while there are changes in behavior from month to month, the general magnitude of the changes stays the same throughout the year. As for the maximum and minimum 1-minute changes shown, these include the forced outages and maintenance outages, and are not only due to changes in the wind speed. The effect of aggregating the output of wind power plants on the 1-minute step changes is displayed in Table 6. Here, the power output from seven wind power plants spread across a large area[11] has been aggregated, then analyzed for the 1-minute changes. As can be seen, the average magnitude of step size, expressed as a percent of total capacity, is about half of what it was for the single 103.5 MW power plant of Table 6.

[11] Spacing between these power plants ranged from 40 to 1500 km.

Table 5. Statistical summary of the magnitude of 1-minute generation changes at a 103.5-MW wind power plant Minnesota, U.S. (Source: Wan 2004)

SW Minn.	Average (kW)	Average (% capacity)	Standard Deviation (kW)	Maximum (+) (MW)	Maximum (–) (MW)
July 2001	399	0.4%	565	16.9	(7.9)
August	384	0.4%	541	22.7	(19.4)
September	384	0.4%	509	7.9	(5.5)
October	549	0.5%	672	7.8	(6.5)
November	434	0.4%	530	14.6	(12.0)
December	464	0.5%	518	12.2	(8.2)
January 2002	475	0.5%	535	5.6	(4.8)
February	491	0.5%	591	17.4	(21.4)
March	449	0.4%	582	6.6	(20.0)
April	564	0.5%	856	14.7	(27.6)
May	554	0.5%	819	18.0	(28.5)
June	631	0.6%	937	16.3	(21.7)
12-month	481	0.5%	657	22.7	(28.5)

Table 6. Statistical summary of the aggregated 1-minute generation changes at seven wind power plants located in Minnesota, Iowa, and Texas, U.S., with a total installed capacity over 790 MW (Source: Wan 2004)

Midwest and Texas Plants Combined					
	Average (kW)	Average (% capacity)	Standard Deviation (kW)	Maximum (+) (MW)	Maximum (–) (MW)
January 2003	1,164	0.2%	1,198	16.9	(45.9)
February	1,516	0.3%	2,134	75.7	(90.5)
March	1,614	0.3%	1,833	45.1	(79.5)
April	1,897	0.3%	2,208	62.8	(96.7)
May	1,652	0.3%	1,811	47.0	(32.8)
June	1,780	0.3%	1,994	30.5	(43.7)
July	1,614	0.3%	1,607	80.2	(32.0)
August	1,391	0.2%	1,507	34.5	(38.9)
September	1,481	0.3%	1,581	31.2	(33.3)
October	1,194	0.2%	1,338	37.2	(37.7)
November	1,434	0.3%	1,828	76.9	(90.1)
December	1,379	0.2%	1,779	43.5	(85.7)
Year	1,508	0.3%	1,767	80.2	(96.7)

2.2.2 Variability in the 10-Minute Time Frame

The next time frame of significant wind power variations to be considered is the 10-minute time frame. Variations within this temporal interval can affect system operation, in particular the regulation and load following. Consistent with the previous tables presented, Table 7 and Table 8 show statistical summaries of the step changes in 10-minute average power output from a single 103.5-MW wind power plant and an aggregate of seven wind power plants of total capacity just over 790 MW (Wan 2004). For a single power plant, the average magnitude of step change in the 10-minute power output was 2.1% of total capacity, whereas it was 1.1% for the combined output of the seven power plants. Compared to the 1-minute changes, the 10-minute changes are more significant. With respect to the effect of aggregating the output of several wind power plants, the magnitude of the step changes as a percent of installed capacity is reduced by about half. The minimum and maximum step changes shown in these tables include the forced and planned maintenance outages and no attempt was made to remove these from the data. Note, although the total capacity is about seven times greater for the output of the aggregated wind power plants, the minimum and maximum 10-minute changes are only roughly double that of the single wind power plant, demonstrating the advantageous effects of multiple and spatially diverse wind power plants on the overall 10-minute variability.

Table 7. Statistical summary of step changes in the 10-minute average wind power at a 103.5-MW wind power plant Minnesota, U.S. (Source: Wan 2004)

SW Minn.	Average (kW)	Average (% capacity)	Standard Deviation (kW)	Maximum (+) (MW)	Maximum (–) (MW)
July 2001	1,849	1.8%	2,552	45.0	(25.6)
August	1,832	1.8%	2,457	38.7	(26.6)
September	1,608	1.6%	2,169	28.4	(28.4)
October	2,396	2.3%	3,050	36.8	(31.3)
November	2,146	2.1%	2,675	43.4	(25.0)
December	2,458	2.4%	2,773	27.5	(34.4)
January 2002	2,509	2.4%	2,810	28.7	(16.2)
February	2,211	2.1%	2,923	48.5	(55.3)
March	2,022	2.0%	2,618	43.5	(27.5)
April	2,214	2.1%	2,931	29.5	(30.6)
May	2,440	2.4%	3,281	28.9	(32.9)
June	2,715	2.6%	3,533	33.3	(35.5)
12-month	2,200	2.1%	2,853	48.5	(55.3)

Table 8. Statistical summary of the step changes in the 10-minute average wind power at seven wind power plants located in Minnesota, Iowa, and Texas, U.S., with a total installed capacity over 790 MW (Source: Wan 2004)

Midwest and Texas Plants Combined					
	Average (kW)	Average (% capacity)	Standard Deviation (kW)	Maximum (+) (MW)	Maximum (–) (MW)
January 2003	5,257	0.9%	5,137	40.8	(80.6)
February	6,455	1.1%	6,992	58.8	(81.1)
March	6,311	1.1%	6,206	64.1	(61.8)
April	6,912	1.2%	7,136	70.9	(68.6)
May	6,456	1.1%	6,685	73.5	(58.1)
June	7,339	1.3%	8,722	80.7	(88.8)
July	6,362	1.1%	6,249	64.9	(62.6)
August	5,293	0.9%	6,247	101.1	(62.8)
September	5,635	1.0%	5,639	47.7	(69.6)
October	5,163	0.9%	5,387	62.0	(64.6)
November	5,693	1.0%	6,439	82.5	(81.7)
December	5,866	1.0%	6,187	56.3	(77.5)
Year	6,053	1.1%	6,501	101.1	(88.8)

2.2.3 Variability in the 1-Hour Time Frame

Wind power variations in the 1-hour time frame are perhaps the most significant when considering wind integration. The reason for this is two-fold: (1) wind power can exhibit significant changes over the course of 1-hour; and (2) many power systems are planned and generation resources committed up to the hour of operation; within the hour, the system is operated with the resources set forth in the hour ahead plan. For example, recall the planning timelines presented in Figure 5 and Figure 6. An example of the hourly step changes in average wind power production at a typical wind power plant is provided in Figure 9. This figure reveals that the preponderance of hourly changes is within ±30% of the installed plant capacity, which is important because it gives the system operator a sense for the variation in wind power that should be expected. However, system operators are responsible for maintaining reliability, and it is often the events (hourly changes) way out in the tails that are of most concern to them, even though they seldom occur. A statistical summary of the hourly step changes at this power plant is provided in **Table 9**. For the 12-month period reported, the average hourly step change was 6.5% of plant capacity with a standard deviation of about the same magnitude. This is about three times the average change of the 10-minute average wind power data. As for the monthly maximums of the positive and negative step changes in hourly average power, the range varies from 30% to 80% of plant capacity depending on the month. A similar statistical summary is presented in Table 10, but for the seven aggregated wind power plants mentioned previously. In comparison to the previous table, the beneficial effects of geographic diversity and aggregation are apparent: the average hourly step change is cut in half to 3.1%, and although the overall capacity is seven times larger than the previous table, the maximum in hourly step changes only approximately doubles. With respect to the maximum changes in wind power from hour to hour, it is of great benefit to the system operator to be able to predict these changes an hour or more ahead of time. Knowing when to expect these large changes to occur can help the system operator manage the costs addressing them.

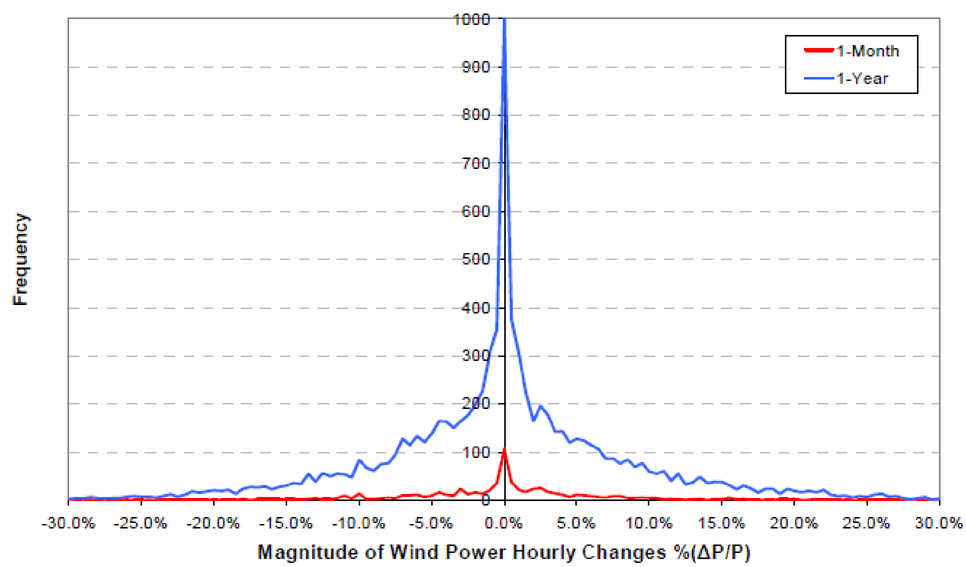

Figure 9. Distribution of hourly step changes as a percentage of capacity for a 103.5-MW wind power plant in Minnesota, U.S. (Source: Wan 2004)

Table 9. Statistical summary of step changes in the 1-hour average wind power at a 103.5-MW wind power plant in Minnesota, U.S. (Source: Wan 2004)

SW Minn.	Average (MW)	Average (% capacity)	Standard Deviation (MW)	Maximum (+) (MW)	Maximum (–) (MW)
July 2001	5.6	5.4%	6.5	31.8	(36.9)
August	5.8	5.6%	6.4	33.0	(47.5)
September	5.2	5.0%	6.1	32.5	(68.6)
October	7.1	6.9%	8.4	66.6	(45.3)
November	6.7	6.5%	7.8	42.5	(47.9)
December	7.5	6.9%	7.7	49.2	(39.4)
January 2002	7.4	7.2%	7.4	40.7	(38.2)
February	7.2	6.9%	8.5	81.6	(57.8)
March	6.3	6.1%	7.4	59.4	(47.8)
April	6.9	6.7%	8.3	58.1	(48.3)
May	7.3	7.1%	8.7	59.4	(73.9)
June	7.2	6.9%	8.3	45.0	(48.8)
12-month	6.7	6.5%	7.7	81.6	(73.9)

Table 10. Statistical summary of the step changes in the 1-hour average wind power at seven wind power plants located in Minnesota, Iowa, and Texas, U.S., with a total installed capacity over 790 MW (Source: Wan 2004)

Midwest and Texas Plants Combined					
	Average (MW)	Average (% capacity)	Standard Deviation (MW)	Maximum (+) (MW)	Maximum (–) (MW)
January 2003	15.2	2.7%	14.0	79.3	(78.2)
February	17.6	3.1%	15.6	80.0	(90.5)
March	20.2	3.6%	17.8	110.0	(121.9)
April	19.8	3.5%	19.0	111.5	(113.0)
May	17.9	3.2%	16.4	103.4	(90.3)
June	20.0	3.6%	19.4	125.1	(126.5)
July	19.1	3.4%	16.4	106.5	(77.7)
August	15.7	2.8%	15.4	141.7	(110.0)
September	17.0	3.0%	14.9	79.3	(78.2)
October	16.3	2.9%	14.0	65.8	(84.8)
November	16.4	2.9%	16.6	113.6	(82.0)
December	18.3	3.3%	16.5	130.0	(93.3)
Year	17.7	3.1%	16.5	141.7	(126.5)

2.2.4 Variability in the Daily, Seasonal, and Yearly Time Frame

Beginning with the daily variations in wind power production, the output of a wind power plant can remain fairly steady or it can range anywhere from no production to full capacity. Figure 10 shows a plot of the 1-minute power data for one week from two 100-MW class wind power plants in the United States (Wan 2004). This figure does a good job displaying the type of daily variability that can occur: on the third day (hours 48 to 72) the power varies from full output, to no output, then back to full output; on the fifth day (hours 96 to 120), the power output remains high most of the day. These variations are of interest, as they provide a system operator with an idea of what to expect for a wind power plant. However, what is most important in determining the impacts of these variations is to know how these modify the load net wind that the system operator must deal with, and the extent to which the variations can be forecasted.

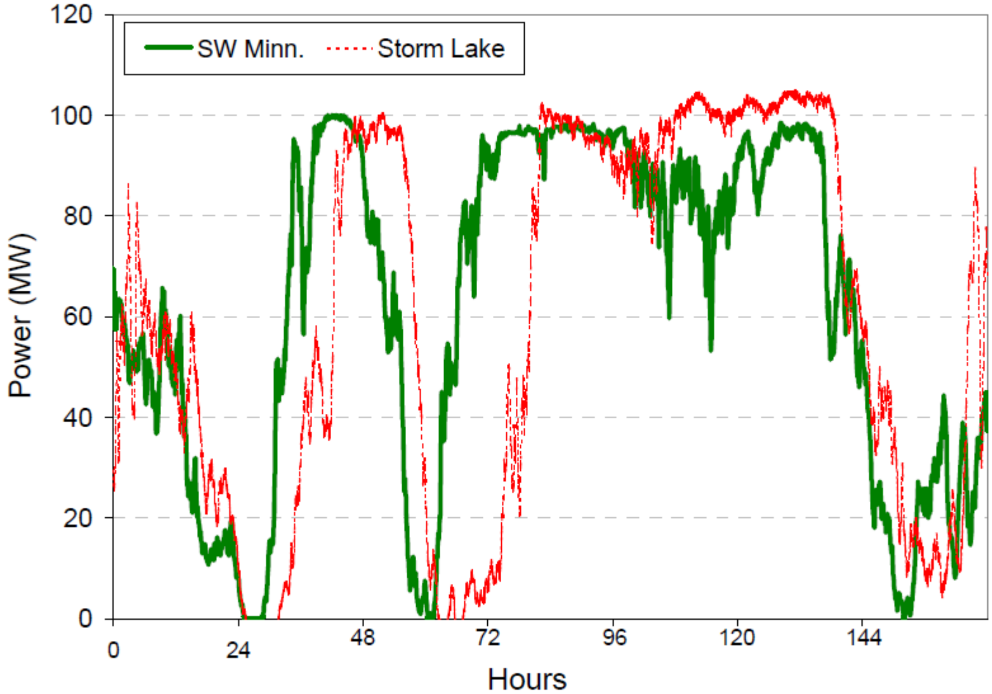

Figure 10. A 1-week trace of 1-minute power output from two wind power plants of nameplate capacity 103.5 MW and 113.25 MW, located 200 km apart (Source: Wan 2004)

The daily variations of a wind power plant often form a consistent pattern, or *diurnal distribution*, with the wind blowing consistently during certain times of the day based upon the meteorology at a given site. Figure 11 shows the diurnal distribution of wind power production at the 103.5-MW wind power plant in Southwest Minnesota, United States, mentioned previously (Wan 2004). The plot on the left side of this figure displays the diurnal pattern during the autumn months over four consecutive years, while the plot on the right considers the summer months. The daily wind patterns show a consistent trend over the years plotted, tending to have a lower production in the early evening. These daily patterns are site-specific and tend to vary throughout the year as the weather patterns shift with the changing seasons. It is important to note that there is significant variability around the diurnal patterns displayed. As an example, consider the plot in Figure 12 showing the monthly average diurnal variation from a small wind power plant during the month of January 2004, and the 1-minute daily power production for every day of that month. The bold, black line that runs approximately horizontally across the plot indicates the diurnal average. At this particular site, there is no diurnal pattern during the month as the winds were driven primarily by synoptic weather fronts and not from daily heating or cooling patterns. The daily traces of wind power shown in this figure give a sense for the variation that can occur from day to day at this wind power plant.

The plots in Figure 13 show the monthly and seasonal variations in wind power production (Wan 2008). Both of these plots show the monthly energy production from wind power plants in Southwest Minnesota (Lake Benton) or near McCamey, Texas, U.S., for several years. One thing to notice from these plots is that there is a consistent pattern of energy production from month to month that is repeated on a yearly basis. This type of consistent seasonal pattern is very common, although the specific shape of it will change from site to site as one considers different locations across the globe. With respect to system planning and operation, *when* the wind power shows up on the system is important both with respect to its marginal value (e.g., higher during peak hours and peak months).

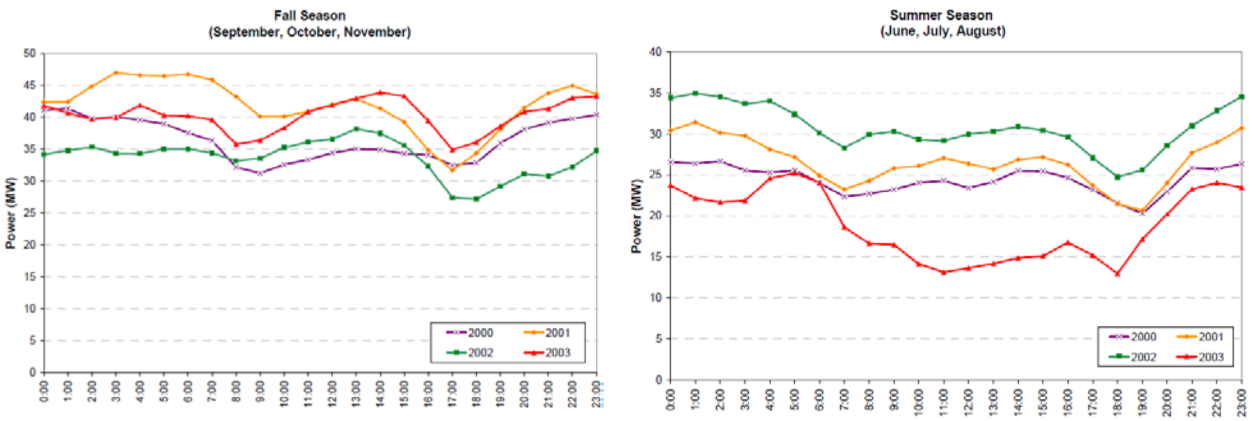

Figure 11. Average diurnal profile of the wind power output of a 103.5-MW wind power plant over three months in the autumn (left) and summer (right), for four consecutive years (Source: Wan 2004)

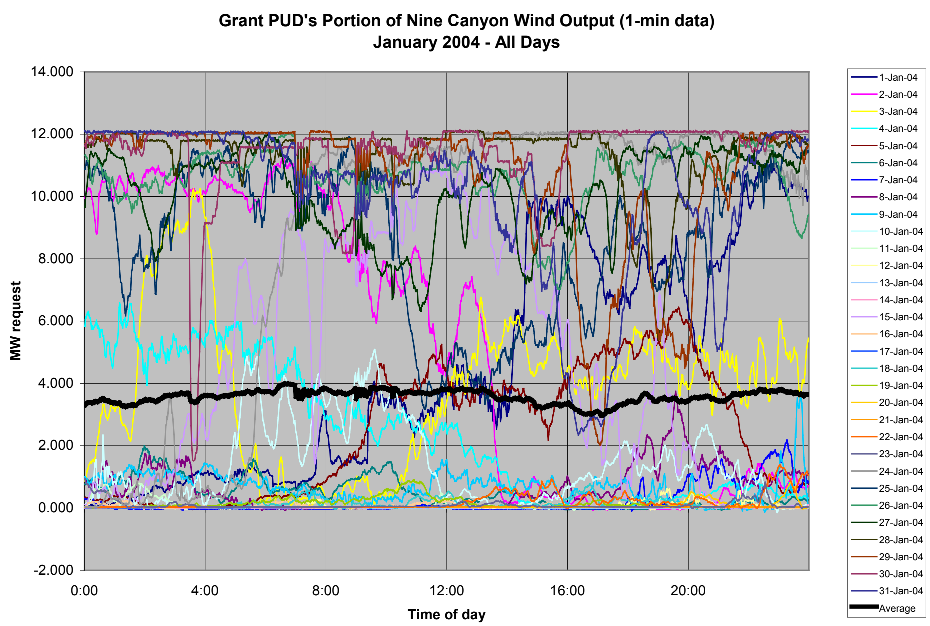

Figure 12. Plot showing the diurnal variation of output from a small wind power plant during January 2004 (Source: Acker et al. 2006)

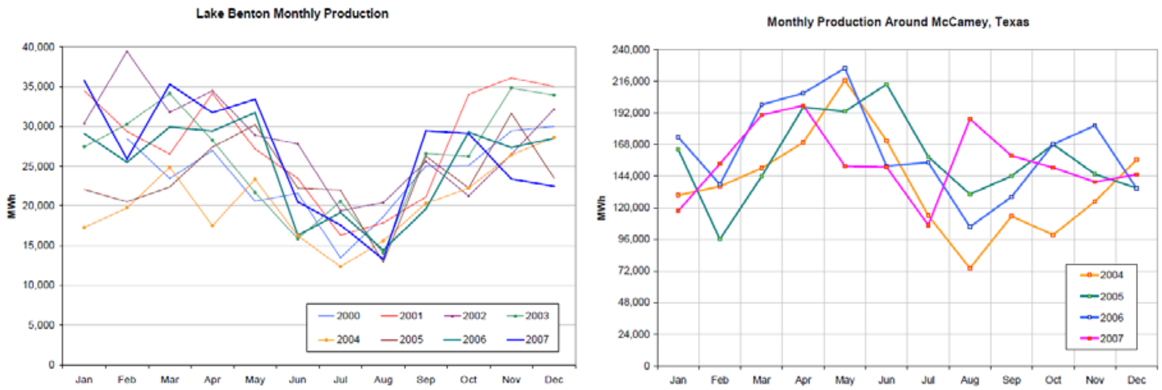

Figure 13. Monthly energy production for a single power plant (left) and for several power plants (right), for several years of operation (Source: Wan 2008)

One can also deduce some useful information about the year-to-year variations in wind energy production from the figures previously presented. Figure 11 shows that the diurnal variations of wind power output follow similar patterns from year to year, but that the magnitude of power production during a given month can vary significantly year to year. This point is emphasized in Figure 13 where large variations in the monthly energy output are evident when comparing the various years plotted. Summing the monthly energy production for these wind power plants near McCamey, Texas, U.S., to obtain an annual value, including summing their aggregate production, then plotting their annual energy output as a percentage of the 4-year average results in the plot shown in Figure 14. Comparing the year-to-year energy output from each wind power plant, the total energy produced varies by approximately ±10% of the average. Note the solid red line on this plot represents the output of all the wind power plants in aggregate, and the aggregate variability from year to year is generally less than for the any single plant in the area.

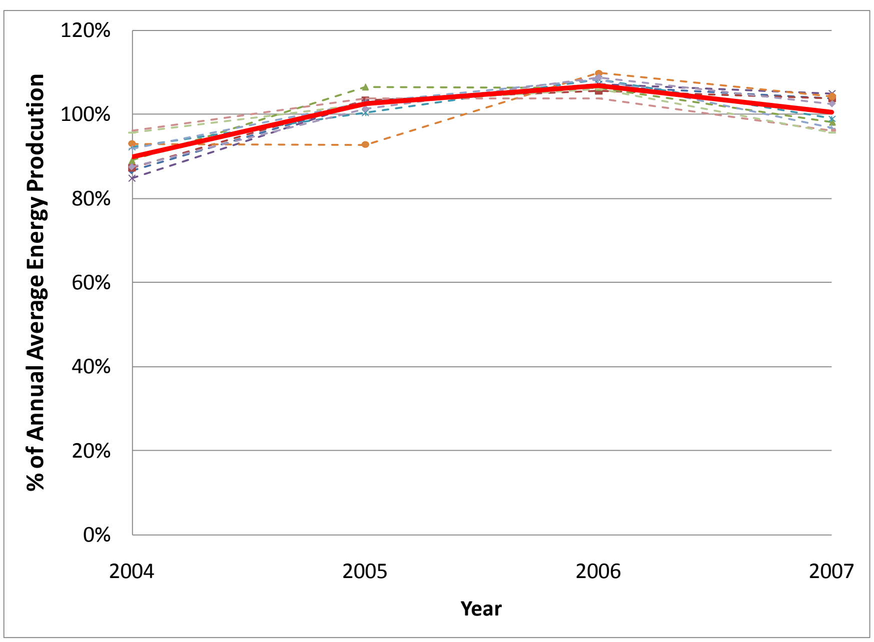

Figure 14. Energy production as a percent of the annual average for several wind power plants near McCamey, Texas, U.S.; the solid red line represents the total energy production from aggregating all power plants together (cumulative nameplate capacity of ~690 MW) (Data source: NREL)

2.3 Characteristics of Wind Power Ramping

Another import aspect of wind plant variability in addition to the step changes in output from one period to the next is how rapidly the wind power may ramp from one output level to the next. The rate at which ramping may occur bears upon the amount of flexible generation a system operator must have access to for maintaining system reliability, which is especially critical within the hour of operation when the availability of flexible generation may be limited. Wan (2004) presents data on wind power ramp rates based upon 1-hour average power output data, defining a ramp rate as the magnitude of change during a time period of monotonic increase or decrease in wind power. Table 11 shows the magnitude of the average, minimum, and maximum ramp rates at the 103.5-MW wind power plant in Minnesota, U.S.. This data is also plotted with the ramp rate as a percent of maximum capacity per hour in Figure 15. Note most of the ramp rates, as defined here, are within ±20% of plant nameplate capacity.

Table 11. Statistical summary of ramp rates at a 103.5-MW wind power plant in Minnesota, U.S., based upon hourly power data (Source: Wan 2004)

	Average Ramping (MW/h)	Maximum (+) Ramping (MW/h)	Maximum (–) Ramping (MW/h)
July 2001	5.7	31.8	-31.0
August	5.6	33.0	-36.1
September	4.8	20.0	-43.4
October	6.7	44.9	-32.6
November	6.4	38.1	-36.9
December	7.2	44.4	-24.0
January 2002	7.3	25.2	-29.9
February	6.6	24.6	-40.3
March	5.9	36.6	-21.8
April	7.0	46.2	-35.5
May	7.4	46.0	-46.8
June	7.5	40.9	-48.8

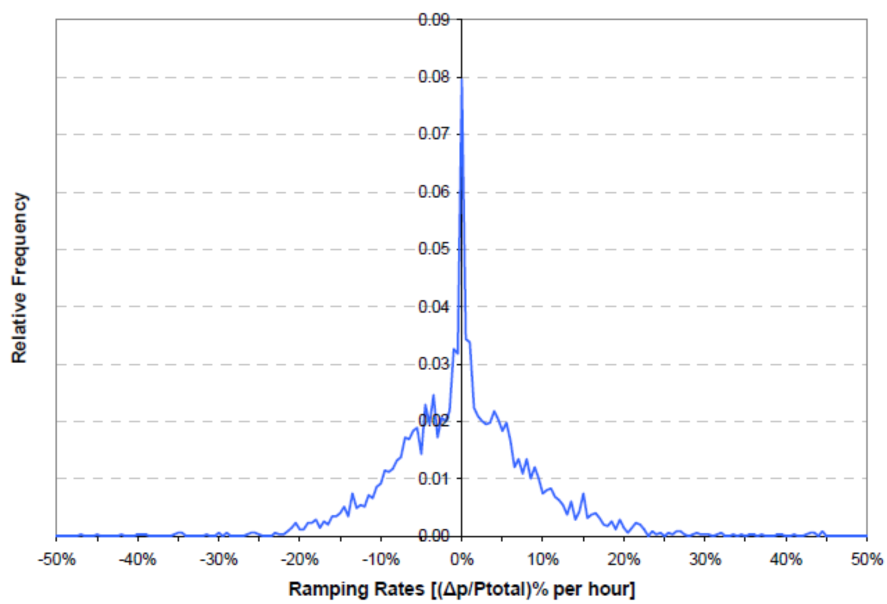

Figure 15. Distribution of hourly ramping rate values (Source: Wan 2004)

Figure 16 provides another method of defining ramp rates at a wind power plant that is more precise. The yellow line in this figure presents the 1-minute power output of a 63.7-MW wind power plant in Washington, U.S., and the blue line is a 15-minute rolling average of this data. The straight, red line segments are the effective ramps, which are defined as periods of monotonic increase or decrease in the 15-minute rolling average, neglecting sign changes of ramps with durations of less than 10 minutes. Ramps defined in this manner tend to represent the general trend in generation consistent with how load is followed within the hour and from hour to hour. Applying this method of defining ramps to 11 months of data from this wind power plant results in the sequence of ramp rates presented in Figure 17. The ordinate on this plot displays the ramp rate as a percent of nameplate capacity per minute, and the abscissa provides the number of ramps during the year. There were approximately 4200 positive and 4200 negative ramping periods, and most of the ramp rates were less than 1% of capacity per minute. In addition to the ramp rate, the duration of the ramp is also of importance as the long, steeper ramps are of greatest potential impact on system operation. For this same set of data, Figure 18 shows the number of ramps of a given duration tabulated versus the absolute value of the magnitude of the ramp. While the specific number of ramps in any particular bin (i.e., of a given duration and magnitude) is not necessarily of interest, the distribution of the ramps is of interest. At this particular power plant, there are very few short duration, high-magnitude ramps, and the preponderance of ramps are of a magnitude less than 30% of the nameplate capacity. Although there are few short-duration, high-magnitude ramps, these few ramps could cause difficulties and incur expense in system operation. The extent to which this occurs, however, depends on the change in the load net wind, the generation resources available, the accuracy of the wind forecast, etc.; in other words, it depends on the operation of the entire system inclusive of the wind power. Fortunately, as increasing amounts of wind energy are brought online, the overall magnitude of the ramp rates as a percent of total installed capacity tend to decline, due to the effects of geographic diversity and aggregation of wind power plant outputs, which is the topic of the next section.

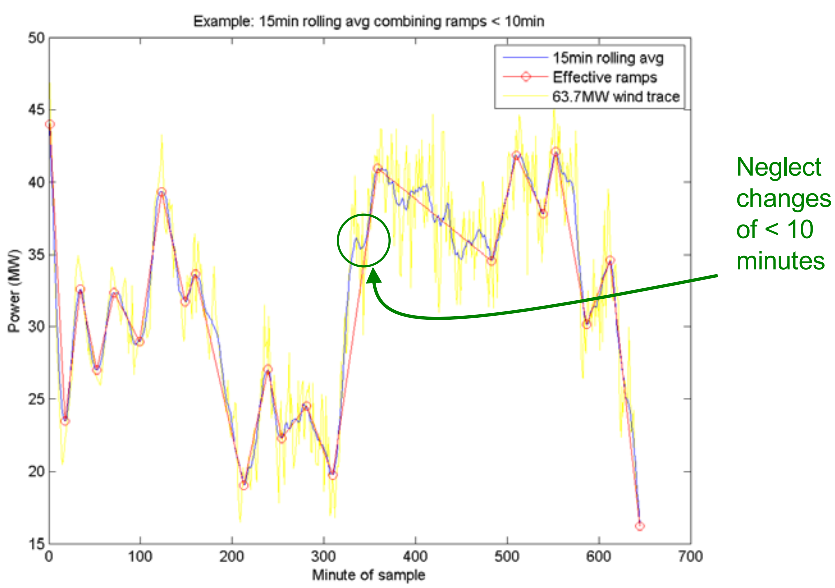

Figure 16. A methodology for defining ramp rates at a wind power plant using a 15-minute rolling average of the 1-minute power output data, neglecting changes less than 10-minutes in duration when defining the end points of the each ramp

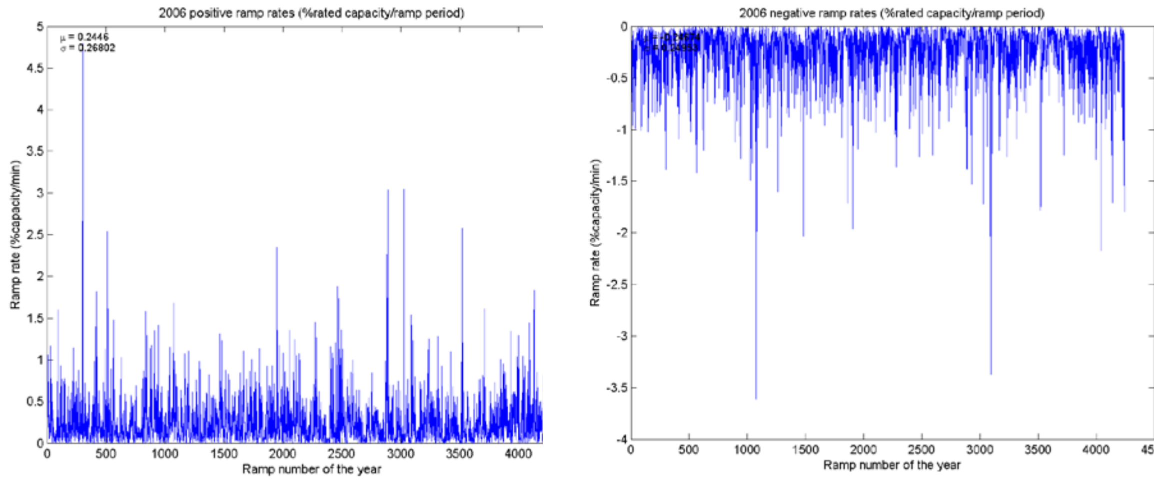

Figure 17. Positive (left plot) and negative (right plot) ramps rates expressed as a percentage of plant nameplate capacity at the 63.7-MW Nine Canyon Wind power plant in Washington, U.S., during 2006

		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200	205
		0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
0	5	0	1	1257	1852	898	667	514	418	310	250	164	137	107	95	66	63	34	34	39	32	17	11	19	18	16	11	15	11	12	8	8	12	9	2	5	5	6	5	3	4	6
5	10	0	0	11	133	162	161	166	151	112	125	92	80	67	48	45	32	34	19	17	15	10	13	8	9	9	3	6	3	4	4	4	4	3	2	2	0	0	4	2	0	0
10	15	0	0	1	17	42	45	41	49	58	38	48	36	34	39	28	25	10	19	14	10	4	12	8	10	8	2	5	5	4	2	4	3	0	2	3	1	0	0	1	1	0
15	20	0	0	0	5	5	27	27	24	22	19	20	19	28	19	19	15	17	14	15	10	11	4	5	1	8	11	1	3	4	2	3	3	1	2	3	1	1	1	0	0	0
20	25	0	0	0	1	6	6	12	9	7	16	16	17	13	14	10	13	12	6	6	8	6	5	4	7	2	4	4	0	2	0	0	0	0	1	0	0	0	0	2	1	1
25	30	0	0	0	0	2	0	5	5	5	11	10	7	3	4	4	8	7	9	4	5	2	3	1	3	7	3	3	3	1	3	0	0	0	3	1	0	0	2	0	1	0
30	35	0	0	0	1	0	2	3	1	5	7	2	4	1	3	3	2	3	1	6	1	3	4	3	3	5	2	4	2	4	0	2	0	0	1	0	0	0	0	2	0	0
35	40	0	0	0	0	0	1	1	2	1	2	0	2	1	5	3	2	2	3	1	1	4	3	1	2	0	1	2	2	5	2	1	1	1	2	1	1	1	2	0	0	0
40	45	0	0	0	0	0	0	1	0	1	0	1	2	1	0	2	2	0	1	2	3	1	1	0	1	1	2	1	1	0	2	1	3	3	0	0	0	0	0	0	0	1
45	50	0	0	0	0	0	1	1	2	0	1	1	2	0	1	1	2	1	0	3	0	2	0	1	0	1	1	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0
50	55	0	0	0	0	0	2	0	1	0	1	4	0	1	0	3	0	0	2	0	0	1	2	2	2	1	0	0	2	1	0	2	0	0	0	0	0	0	0	0	0	0
55	60	0	0	0	0	1	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	1	1	0
60	65	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
65	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

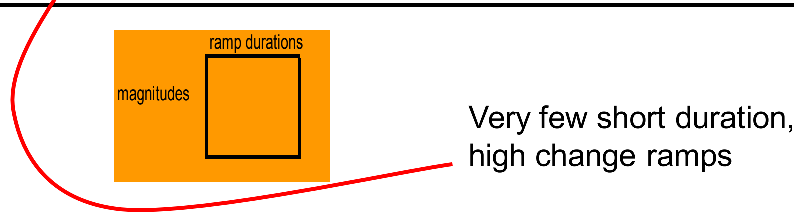

Figure 18. Table demonstrating the distribution and duration of ramp events at the 63.7-MW Nine Canyon Wind power plant in Washington, U.S., during 2006 (magnitudes are in megawatts and durations are in minutes)

2.4 Impact of Geographic Diversity and Aggregation of Wind Power Plant Output on Wind Power Variations

Aggregating the output from numerous wind power plants tends to have a beneficial effect on the overall variability of the wind power being absorbed into a power system. This effect has been demonstrated via the results presented in Section 2.2, where the changes in output expressed as a percent of nameplate capacity per period (minute, hour, etc.) became smaller as the output was combined from multiple, spatially diverse wind power plants. That is, the variations that may occur at a single wind power plant do not scale up linearly. The basic reason for this non-linear scaling effect is that the power outputs from spatially diverse power plants become less and less correlated as the spacing between them grows, and therefore more and more of the changes in power output at one power plant are to some extent countered by an opposite change in output at another power plant. This effect is evident at all spatial scales from groups of turbines within a single power plant that have a higher level of correlation to geographically distant wind power plants where the output may be completely uncorrelated. For example, consider the data shown in Table 12 (Wan 2005). The 14-, 61-, and 138-turbine groupings shown are from wind turbines at a single power plant, and the 250+ turbines represent the combined power output of two nearby power plants (including the 138 turbines). As demonstrated in this table, as more turbines are considered and the nameplate capacity of the turbines increases, the average magnitude and standard deviation of the step changes in wind power generally increase in magnitude, but generally decrease as a percentage of overall installed capacity. The magnitude of the numbers shown in this table will vary from site to site, but with consistent trends. Wan (2005) also shows that similar trends apply to the wind power ramp rates as for the step changes in power output.

Table 12. Step changes in wind power output from groupings of wind turbines located in Minnesota, U.S. (Source: Wan 2005)

		14 turbines		61 turbines		138 turbines		250+ turbines	
		(kW)	(%)	(kW)	(%)	(kW)	(%)	(kW)	(%)
1-second									
	Average	41	0.4	172	0.2	148	0.1	189	0.1
	Std Deviation	56	0.5	203	0.3	203	0.2	257	0.1
1-minute									
	Average	130	1.2	612	0.8	494	0.5	730	0.3
	Std Deviation	225	2.1	1,038	1.3	849	0.8	1,486	0.6
10-minute									
	Average	329	3.1	1,658	2.1	2,243	2.2	3,713	1.5
	Std Deviation	548	5.2	2,750	3.5	3,810	3.7	6,418	2.7
1-hour									
	Average	736	7.0	3,732	4.7	6,582	6.4	12,755	5.3
	Std Deviation	1,124	10.7	5,932	7.5	10,032	9.7	19,213	7.9

The variability of the output in wind power plants is an important consideration in power system operation. Also of significance is the magnitude of the wind power output itself, and the relationship between the power output at geographically separated wind power plants. For example, how likely is it that numerous wind power plants be producing near their full output at the same time, or at no output? One might expect the output of wind power plants in the same general region, affected by the same weather patterns, to have a similar production pattern. However, as wind power plants become further separated, their output will be impacted by differing weather systems or topographical features, and one might expect their output to not be correlated. Wan (2005) considered the correlation coefficient between the power output at spatially separated wind power plants in the Midwestern U.S., resulting in the plot shown in Figure 19. There are four lines shown on this plot: one for the 1-second, 1-minute, 10-minute, and 1-hour average power production at the spatially separated power plants (note the logarithmic scale for the distance between the power plants on the abscissa). As shown, there is no correlation in the 1-second power output even for nearby power plants, and little correlation in the 1-minute power output. The correlation coefficients become larger for the 10-minute and

1-hour time series for nearby power plants, diminishing to zero for geographically distant power plants.

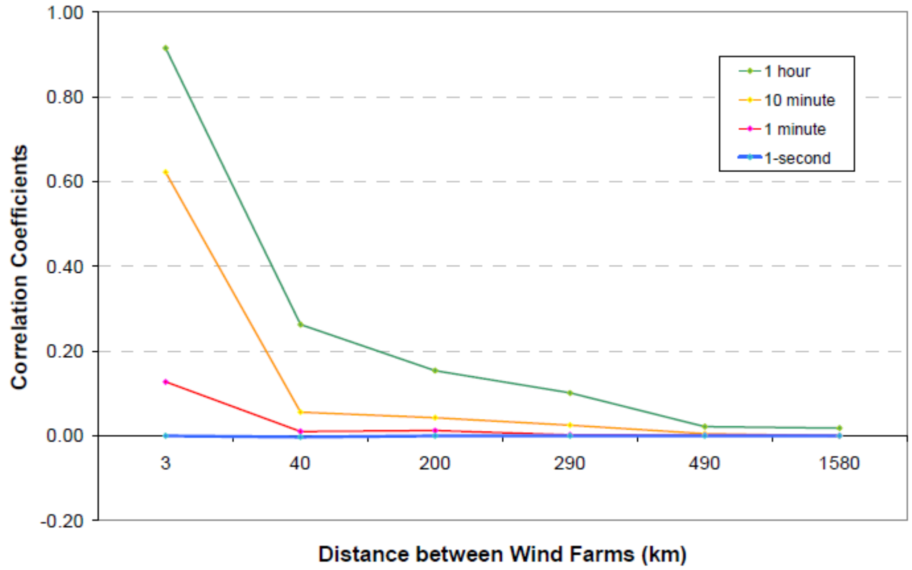

Figure 19. Correlation coefficient between spatially separated wind power plants plotted as a function of the distance between them, for their 1-second, 1-minute, 10-minute, and 1-hour average power outputs (Source: Wan 2005)

2.5 Wind Power Forecasting and Uncertainty

As the previous sections of this chapter have demonstrated, there is a significant amount of variability associated with the generation from wind power plants. This variability occurs on all time frames of power system operation (seconds to years), with perhaps the most important variations occurring in the 10-minute, 1-hour, and 1-day time frames. However, whether or not these variations cause significant impacts or incur appreciable costs depends upon many factors, such as the characteristics of the system load and generation, the penetration and characteristics of the wind power, the flexibility of the market, etc. As for the costs and implications on system reliability, one can imagine that if the wind power output and its variations can be well predicted, then the overall impact and cost of those variations can be minimized. To the extent that there are errors in the wind forecast that increase the uncertainty in the load net wind (i.e., the effective load signal that the system operator must balance with generation), additional reserves must be set aside to prepare for potential deviations between the forecast and actual load net wind. Thus, wind power forecasting is of significance in power system operation and modeling, and it is the purpose of this section to provide a brief overview of the state-of-the-art and implications on system operation.

There are three basic approaches by which wind power forecasts are created: physics-based numerical weather prediction (NWP) models, statistical models or combinations of the two (Costa et al. 2008, Zack 2009). NWP models in use today include Mesoscale Model Version 5 (MM5), the Weather Research and Forecasting Model (WRF), the High Resolution Limited Area Model (HIRLAM), etc. These models solve the complex equations of motion that govern atmospheric flows to produce predictions of weather variables such as the wind speed, direction, temperature, pressure, etc., which can then be converted to a prediction of the power output. The particular forecast approach one would use (NWP, statistical, or combination) depends upon the time frame of the forecast (i.e., the number of hours ahead of time for which the prediction is made). For very short-term forecasts, minutes ahead up to an hour, statistical methods that rely on recent wind speed and power production data dominate, for example using an auto regressive moving average model to predict future power output. From an hour ahead to several hours ahead, the forecast method might rely on an autoregressive prediction combined with an NWP model and off-site data, and potentially use some type of genetic algorithm to improve forecasts based on previous performance. Beyond several hours ahead of time, the state-of-the-art is represented by NWP models that are statistically corrected to better match the actual power production at a given site (e.g., using model output statistics). The performance of a single, deterministic prediction based on an NWP can be improved upon by ensemble averaging. In this type of averaging, the input conditions and assumptions are modified in some fashion within their range of uncertainty, and the NWP model is re-run. After performing multiple runs, the outputs of the NWP are then averaged or otherwise combined, typically resulting in a better performing forecast. Ensemble averages can also be produced when using purely statistical techniques, or by combining both statistical and NWP methods.

Wind power forecast models can be set-up to provide a "deterministic" forecast, such as a single most-likely value, or a "probabilistic" forecast that predicts not only a most-likely value but also confidence interval. For example, see Figure 20 from Ernst et al. (2007). The basic idea with a probabilistic forecast is to provide more information to the system operator from which to make decisions. At present, addressing the issue of how to best integrate wind forecasting into system planning and operation is a work in progress, and wind forecast providers are working with system operators and others to devise useful methods to bring wind power forecasts into system planning and the control room.

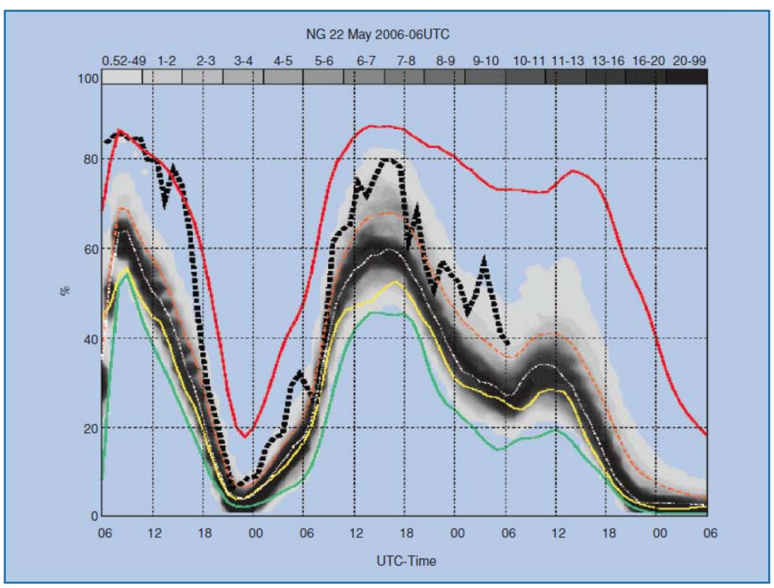

Figure 20. Plot of a wind power forecast from WEPROG's MSEPS system (see www.weprog.com/) including uncertainty bands (black and gray shading); a few methods of predicting the expected output (orange dashed, white, and yellow lines); and the predicted maximum and minimum possible values (top red and bottom green lines)—the actual output is shown by the bold, black, dashed line (Source: Ernst et al. 2007)

Any power system that incorporates significant amounts of wind power probably either uses a professional wind forecast based upon an NWP model, or is interested in doing so. General Electric, in its study of integrating wind power into the New York independent systems operations, showed that the value of a state-of-the-art “professional” wind forecast improved the value of wind energy by about 25% (Piwko 2005), or $10.70/MWh of wind energy produced, relative to using no forecast at all. This value was attained by including the wind forecast in the day-ahead commitment process of the cost production simulation, in effect reducing the planning uncertainty and permitting more economical use of the existing system resources to meet the load net wind. Barthelmie et al. (2008) presents a study of short-term wind forecasting in the United Kingdom electricity market, and similarly shows an economic benefit to wind power forecasting.

As for the performance metrics that describe the accuracy of a professional forecast, the mean absolute error (MAE) or the root mean square error (RMSE) are the most frequently cited. The MAE is computed by determining the forecast error for the forecasted hours hour being considered (e.g., typically one year or more), taking the absolute value of these errors, and then calculating the mean. The RMSE is slightly different; it is calculated by finding the difference between the forecasted and actual wind power generation for each hour of the time period under consideration, squaring this difference, summing these squared values, and computing the average, then taking the square root of this average. Because the difference is squared in this calculation, large errors in the forecast are weighed more heavily, and the RMSE is greater than the MAE. For a typical professional forecast, both the MAE and RMSE are relatively low for short-term forecasts, reflecting overall accuracy in the mean. For example, the plots in Figure 21 show the MAE (plot on the left) and the RMSE (plot on right side) for a relatively small (~ 60-MW) wind power plant in the United States. Both of these plots show the error plotted versus time horizon of the forecast, varying from 1 hour ahead to 50 hours ahead. There are three forecast methods plotted: climatological (in this case, forecasting the output to be the annual average); persistence (the forecast for any future hour is equal to the wind power production during the last hour); and professional (based on an NWP and/or statistical models and field data). The professional forecast shown represents a state-of-the-art forecast in the period from 2004–2006; three years of data were used to create these plots.

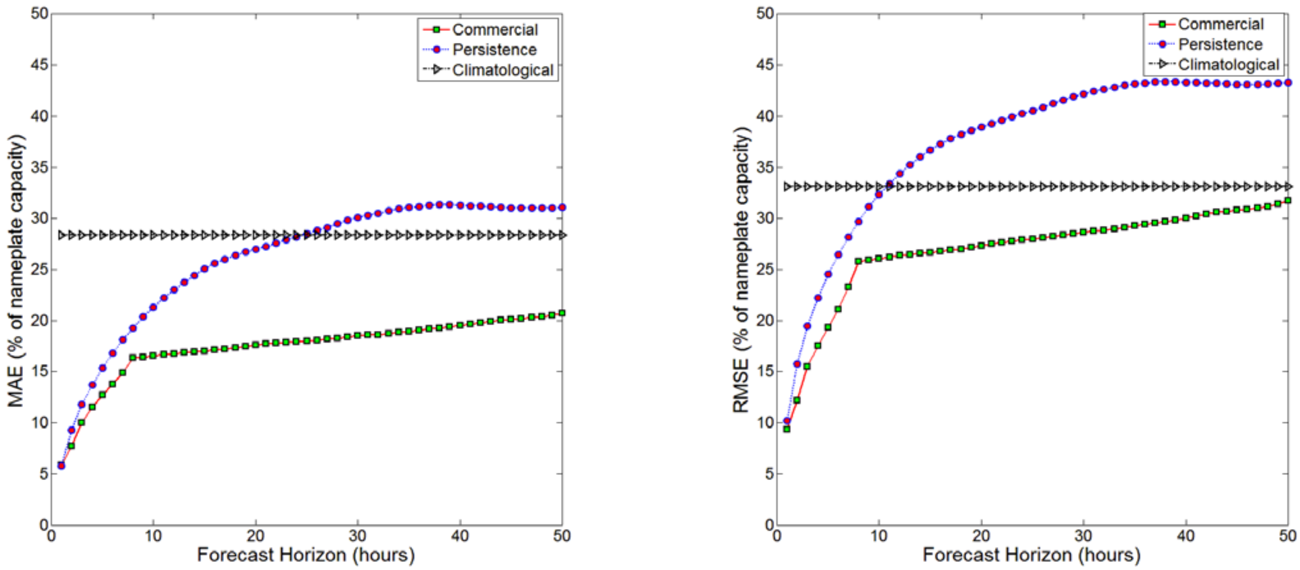

Figure 21. Plots of the MAE and RMSE versus the number of hours of lead time for the forecast, for a wind power plant in the United States; the errors for three types of forecasts are displayed: professional, persistence, and climatological (Source: Northern Arizona University)

System operators and planners are concerned with being able to securely operate the system during all hours of the year, and are therefore keenly interested in the "outlier" events where the wind forecast may be greatly in error and the ability to maintain system reliability may be tested. Figure 22 shows a graph of the hour-ahead MAE for the same professional wind forecast as displayed in the previous figure, but sorted by the hourly change in wind power production. Note the overall MAE for the hour-ahead wind forecast denoted by the red "+" matches the hour-ahead forecast error from Figure 21. As one considers increasing magnitudes of hourly changes in wind output, the MAE of forecast error during these hours becomes increasingly large. However, as the black line indicates, there are relatively few hours during the year when these large hourly changes occur. A few observations can be made from this figure: (1) the forecast errors at the various levels of hourly change are roughly symmetric about zero; (2) when there are small hourly changes in wind power output, which is most hours of the year, the MAE is quite low; and (3) when significant changes in power output occur, the system operator and planner need to plan additional reserves due to uncertainty in the output, whereas when there are small changes in output forecasted, there is more certainty in the forecast and less reserve need be set aside. Note, for larger wind power plants, or where several wind power plants are aggregated in a balancing area, the overall magnitude of the MAE in each bin will likely reduce. Figure 23 presents another way of displaying this information. Here, the plot is made with the same data but using the absolute value of the hourly change on the abscissa. It is perhaps more obvious on this chart the difficulty in forecasting wind power during large ramping events, and that these events occur very infrequently. Note for very large hourly changes in generation that the MAE is quite large. One current area of research in wind forecasting is improving forecast performance (reducing the MAE or RMSE) for hours where the generation changes are large, essentially predicting the large wind power ramping events better. Concerning the system operator, understanding when to look out for large ramp events (and when not to) is key to minimizing the cost associated with wind forecast errors.

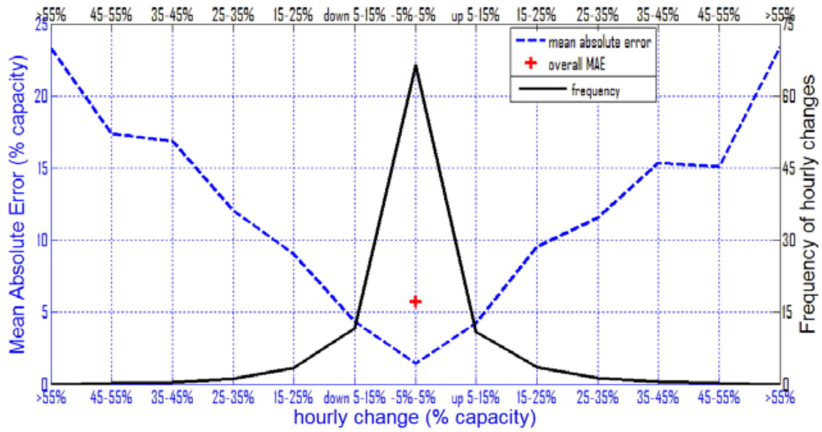

Figure 22. Plot of the hour-ahead mean absolute error, sorted by the hourly change in output of the wind power plant; the blue, dashed line corresponds to the mean absolute error, the black line denotes the frequency of occurrences in each bin of hourly changes, and the red cross identifies the overall mean absolute error (for all hours, regardless of hourly change) (Source: Northern Arizona University)

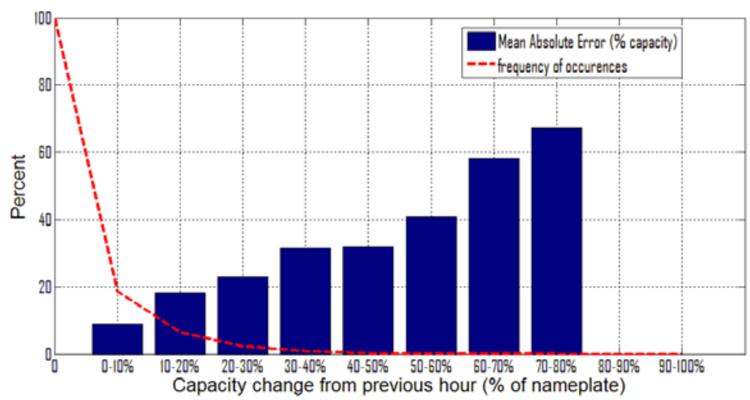

Figure 23. A plot demonstrating the hour-ahead MAE and cumulative frequency count as a function of the hourly change in wind power plant output (Source: Northern Arizona University)

As was mentioned with respect to the variability of the wind power in the previous sections, it is the overall variability of the load net wind that is of importance to the system operator and planner, and not the variability of the wind power by itself. The same is true for the forecast error. Just as the system planner and operator must address the variability of the load net wind, so too must they plan for the combined forecast error of the load and the wind power. Thus, the overall impact of forecast error and variability must therefore be addressed in the context of the entire system, its resources, characteristics, and loads.

2.6 Capacity Value of Wind Resources

As mentioned previously in Section 2.1, the capacity value of a wind power resource is related to its power production during the peak hours of the year. To the extent that wind power is available during the peak hours, it can displace the need to build other capacity resources on the system and thus has a capacity value. No single method is agreed on for computing a capacity value of wind resources; however, a common method to determine the capacity value of a wind power resource is to compute the ELCC, which is defined as the amount of additional load that can be served at a prescribed reliability level with the addition of a given amount of generation. This ELCC is based on one of several reliability metrics, such as the loss of load probability or the loss of load expectation. Determining the ELCC can be accomplished using a power system reliability model, and is fairly data intensive. Milligan has suggested an alternative, approximate method to determine the capacity value of wind power (Milligan and Porter 2007, Milligan and Parsons 1997). While this method is not a substitute for utility techniques of computing the ELCC of a generator (or some other similarly rigorous technique), it has been shown to provide a fair indication of the wind's capacity value, within a few percent. The basic idea of this technique is to compute the average capacity factor during the highest 10% of load hours during the year. Taking this value of the capacity factor and multiplying by the nameplate capacity then provides an approximation of the capacity value from the wind power plant. Two points of interest generally emerge from application of this method: (1) the capacity value will normally be less than the average capacity factor for the entire year; and (2) the wind power will have a capacity value that is a significant fraction of its average capacity. The capacity value of wind has been shown to range from approximately 10% to 40% of the wind-plant rated capacity (Smith et al. 2007). Some of the data shown were computed using the ELCC method, and others used simplified methods, such as suggested by Milligan.

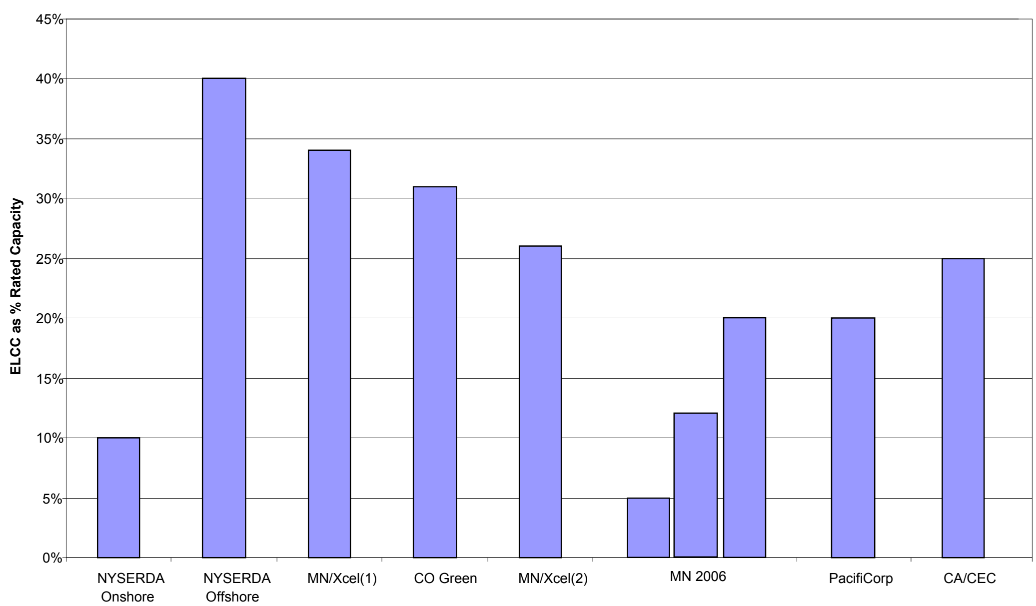

Figure 24. The capacity value of wind power as determined in several wind integration studies in the United States (Source: Smith et al. 2007)

2.7 Environmental Attributes

Wind energy, like every generation resource, has environmental impacts. On the positive side, wind energy does not produce any pollutant air emissions and requires no water, the latter of which is of importance in arid regions of the world. Indeed, one of the positive benefits of using wind power is that to the extent it displaces thermal power generation, it avoids emissions and water use. The negative impacts of wind energy include noise, visual impacts, and avian and bat mortality. With respect to noise, modern wind turbines that have relatively slow rotation rates (<20 revolutions per minute) tend to be fairly quite. However, depending on the proximity to people or wildlife, noise may still be an issue. These visual and noise impacts, as perceived by any given community, can often be minimized through proper siting and must be considered during the public permitting process that accompanies siting of a new wind power plant. Perhaps the most significant environmental impact is that due to avian and bat mortality. Design improvements over the past several years, such as using monopoles (no lattice towers) and reducing the blade rotation rate, have significantly reduced the impact on mortality. Furthermore, appropriate siting can help avoid poor locations where some bird species may be at risk, such as migratory flyways. Bat mortality has recently become a problem at some North American wind power plants, and is an active area of research and concern (Kunz 2007, NWCC 2004).

2.8 Summary of Wind Variability and Uncertainty: Considerations in System Planning and Operation

In this chapter, several important aspects to wind power were presented. When considering wind power, there are several contributing factors to its overall value in the power system. The collective impacts of these factors typically lead to a net positive economic value, acknowledging that there may be instances when this is not the case, dependent upon the specific utility or electrical system and its market. One of the cost components of wind energy is the “integration” cost, due to the effects of wind power’s variability and uncertainty on system operation. NREL (Wan 2004, 2005, 2008) has published some insightful reports describing the variability of wind power, based on the output of actual wind power plants in the United States. The data presented in this chapter was intended to provide a sense for the order of magnitude and frequency of power output changes with which a system operator or planner must contend. The data suggest that there will be a relatively small impact at the regulation (minute to minute) time scale, but becoming considerable at the hourly time scale and beyond (e.g., load following, unit commitment, reserve requirements). In addition to being variable, wind power is also uncertain, and though accurately predictable much of the time, can suffer from large forecast errors that may occur at inopportune times during system operation. Wind power, while primarily an energy resource, does have a capacity value that should be considered in system planning. Another positive aspect of wind energy is its environmental attribute of being a carbon-free, water-free energy generation technology. What makes wind power different to a system operator and planner as compared to other power resources is its variability and uncertainty, and learning how to understand and work with these characteristics. The overall impact of the wind power variations, forecast errors, and their associated integration cost, combined with the cost of wind energy, its marginal value, and the positive benefits it brings to the electrical system, depend on a host of factors, including the system load, the generation fleet, operational and market flexibility, etc., and can only be accurately estimated via a thorough cost production simulation of the power system. The methods employed in carrying out such a simulation are presented in Volume 2, Chapter 1, of the Task 24 report. Results of such studies pertaining to wind and hydropower integration will be discussed in Chapter 4.

3 Hydropower System Planning and Operation

3.1 Introduction

Hydropower was one of the original and principal sources of electrical energy in the early and mid-20th century. Since then, the world's electricity production has become predominantly fossil fuel based, and with energy demand continuing to escalate, pressures on the world's climate and general environmental well-being are also growing. In most countries, hydropower's role is a smaller percentage (in terms of overall energy production) than in the past, although it is often important for the provision of ancillary services, including storage. One reason hydropower is used less often now than in the past is that it takes less time to design, approve, build, and recover investment from thermal power plants, which are also less constrained in their operation. However, thermal power plants have higher operating costs; typically shorter operating lives (about 25 years); are sources of air, water, and soil pollution and greenhouse gases; and provide fewer opportunities for economic spin-offs. In assessing life cycle costs, hydropower consistently compares favorably with virtually all other forms of energy generation, and is therefore a preferred power resource.

Over the last two decades, the development of new hydropower projects as well as the modernization of existing plants, while still significant, has been under increasing pressure for a variety of financial, environmental, social, and regulatory reasons. However, hydropower's role in integrating other renewable energy sources, especially wind energy, has the potential to grow both in extent and importance. While fluctuating power levels and transmission constraints have hampered ready adoption of wind energy to the utility grids worldwide, fluctuating water levels, growing pressures on water supplies, the need for flood controls, and environmental issues are just a few of the constraints that may limit future growth of hydroelectric production.

Hydropower provides unique benefits rarely found in other sources of energy. These benefits can be attributed to the electricity itself or to side-benefits, often associated with reservoir development.

Despite the recent debates, few would disclaim that the net environmental benefits of hydropower are far superior to fossil-based generation. While development of all the remaining hydroelectric potential could not hope to cover total future world demand for electricity, implementation of even half of this potential could have enormous environmental benefits in terms of avoided generation by fossil fuels, especially if deployed in a manner in which the hydro flexibility can support the additional ancillary services requirements brought about by wind power or other variable renewable energy resources.

Generally speaking, several attributes of hydropower are as follows:

1. Hydropower resources are widely spread around the world. The potential use of hydropower exists in approximately 150 countries, and about 70% of economically feasible areas remain to be developed, which is primarily in developing countries.
2. Hydropower is a proven and well-advanced technology with more than a century of experience, and modern hydropower plants are capable of very efficient energy conversion (>90%).

3. Hydropower plays a major role in reducing greenhouse gas emissions in terms of avoided generation by fossil fuels. Hydropower is a relatively minor source of atmospheric emissions compared with fossil-fired generating options.
4. The production of peak load energy from hydropower complements the base load power from other, less flexible electricity sources. Hydropower's fast response time enables it to meet sudden fluctuations in demand.
5. Hydropower has the lowest operating costs and longest plant life compared to other large-scale generating options. Once the initial investment has been made in the necessary civil works, plant life can be extended economically by relatively inexpensive maintenance and the periodic replacement of electromechanical equipment (e.g., replacement of turbine runners, rewinding of generators) and, in some cases the addition of new generating units. A hydro plant in service for 40–50 years can typically have its operating life doubled.
6. Hydro plants are very often integrated within multipurpose developments, which are satisfying other fundamental human needs (e.g., irrigation for food supply, domestic and industrial water supply, flood protection). Reservoir water may also be used for other functions such as fisheries, discharge regulation downstream for navigation improvements, and recreation.
7. Hydro plants' "fuel" (water) is renewable, and is not subject to fluctuations in market conditions. Hydropower can also represent energy independence for many countries.
8. Positive engineering attributes of hydropower include integrated controllability and response time of generators, transmission systems linking the physical locations of the hydropower with the system load, and the characteristics of the utility electric load.
9. The capacity of the reservoirs and the seasonal and yearly inflow variability for dry, normal, and wet years is an important consideration in long-term planning of hydro generation.
10. In comparison with hydropower, thermal plants take less time to design, obtain approval for, build, and pay back. However, they have higher operating costs; typically shorter operating lives (~25 years); are key sources of air, water, soil pollution, and greenhouse gases; and provide fewer opportunities for economic spin-offs.

The purpose of this chapter is to describe the aspects of hydropower relevant to wind and hydropower integration, establishing what is unique about hydropower relative to other flexible power resources used for system balancing or energy storage, and helping set the context for the results to be described later in this report.

3.2 Types of Hydropower and Energy Storage

Many renewable energy technologies are variable in nature, meaning they are not continuously available, because they rely on the wind or sun. All hydroelectric generating plants, except for the very smallest can, to a greater or lesser extent, store water and therefore energy, and then release it to generate electricity when required. This ability to store energy is an asset that can be combined with other renewable technologies like wind energy to enable larger-scale use of renewable energy. Hydropower owners can also use this as a source of revenue.

3.2.1 Hydro Storage

The fundamental principle of a hydropower plant is to construct a barrier (dam, dyke, or barrage) across the flow of a river, store the water behind this barrier, and generate electricity through hydraulic turbines when there is a demand for the energy (see Figure 25). If more water flows down the river than can be used for generation, the excess water flows over the spillway across the top of the dam or through sluices of various types. Therefore, the design of many hydro-electric developments has, in the past, been based on optimizing generation (and spill avoidance) versus storage, with the result that many projects with high dams and very large storages have been developed. This objective is concomitant with flood control. These large storage projects can have the greatest potential for significant system integration with wind power in terms of storage (shifting water and energy releases for days to months) and ancillary services. For example, if excess wind generation is available, it may be possible to reduce the flow through a hydropower facility and save it for a later time. Hydro projects with small reservoirs may also possess decent potential for integration with wind, though mainly in providing ancillary services related to the shorter time scales (regulation, load following, reserves), but also via energy storage from hours to a couple days. In mountainous areas, with high precipitation (snow fall and/or rain), many large hydro plants have small storages and modest flows, but high hydrostatic heads[12]. These hydro plants often use slow snowmelt as their primary storage mechanism, and similarly, may be capable of providing ancillary services on shorter time scales.

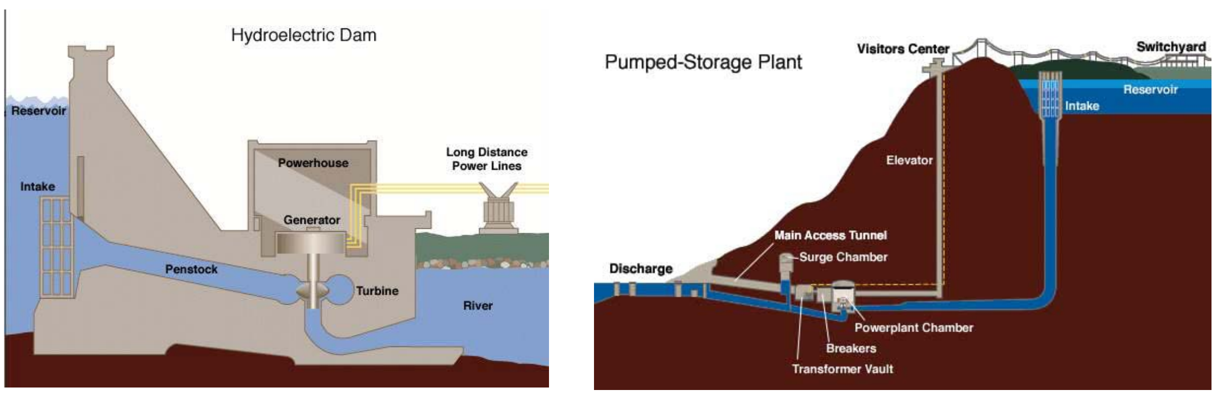

Figure 25. (a) Typical configuration of a dam and hydropower plant; (b) a pumped-hydropower plant (Source: Tennessee Valley Authority, www.tva.gov/power/hydro.htm)

The typical setup of water impoundment behind a dam with hydro turbines is not the only possible water storage configuration. In some cases, storage is sometimes augmented by large, on- or off-stream storages, using barriers placed across rivers or lakes to provide additional storage without hydropower generation at the site. The flows can be released as required, and connected to the hydro developments by tunnel or canal, or along the original waterway.

3.2.2 Run-of-the-River Hydro

Run-of-the-river hydropower plants are constructed with the aim of using hydropower for generation of electrical energy without the construction of large water impoundment reservoirs. A "pure" run-of-the-river hydro plant would have no storage at all and simply use water as it comes down the river. However, in most cases, some level of storage is associated with a run-of-

[12] The term *head* often refers to the height of the reservoir surface above the generators. The higher the head is, the greater potential for power generation (power = head height × flow rate of river × efficiency of generators).

the-river dam, varying from several hours to 2 weeks of flow in the river. Often, when run-of-the-river hydro is employed on a river, there will be several dams and power plants leading to the building of reservoir cascades along rivers (i.e., several run-of-the-river hydropower plants in succession on a single river). The illustration of a hydropower facility shown in Figure 25 is most like a run-of-the-river hydro plant, with a relatively low height of the dam.

3.2.3 Pumped Storage

Pumped hydro-electricity storage is one of the oldest and largest of all the commercially available energy storage technologies. It is a method of storing and producing electricity to meet high-peak demands, working on a simple principle. As shown in Figure 25, two reservoirs at different elevations are required. When the water is released from the upper reservoir, the downward flow is directed through high-pressure shafts, linked to turbines, which in turn power the generators to produce electricity. In storage mode, water is pumped to the upper reservoir by reversing the generators and running them as motors. About 70% to 80% of the electrical energy used to pump the water into the elevated reservoir can be recovered in this process. A typical mode of operation for such a plant is to pump the water during off-peak hours when electricity is inexpensive, and then release the water during on-peak hours when the value of the electricity is very high (a process referred to as *load factoring*). Assuming an 80% "round trip" efficiency, the minimum price differential between the off-peak and on-peak electricity must be $(1 \div 0.8) = 1.25$ in order for the pumped hydro to be affordable; in other words, the cost of running a pumped hydro facility cannot break even unless the on-peak price is at least 25% higher than off-peak. If the roundtrip efficiency is 70%, then this percentage increases to 43%. Even with this requirement, as a system resource (i.e., a resource that is valuable in balancing the overall variations of load in a balancing area), pumped hydro can be a cost-effective peaking resource.

With respect to providing the enhanced ancillary services as required by wind integration, pumped hydro is a viable option only if its ability to provide ancillary services is more valuable than the load factoring it currently provides. One wind integration study conducted in the United States for a utility in Colorado considered the value of a large (>300 MW) pumped storage facility in reducing wind integration costs (Zavadil 2006). At a 10% penetration of wind energy (wind capacity divided by peak load), the benefit of pumped hydro was small, and suggested that new investment in pumped hydro for the benefit of wind integration would not be cost effective. As such, the prevailing opinion is that pumped hydro, due to its large capital costs, will not likely be cost effective for wind integration until wind penetration levels get quite large (30% to 50%). For this reason, storage in this study focuses on conventional hydro, in which no efficiency penalty is incurred as it is for pumped hydro, and the storage is accessed by altering flow schedules through the generators and retaining water in the reservoirs.

3.2.4 Other Non-Hydropower Storage

3.2.4.1 Flow Batteries

Flow batteries, or regenerative fuel cells, can store and release energy through a reversible electrochemical reaction between two salt solutions (electrolytes). These systems are good for storage of real power (megawatts), but poor for quick delivery of reactive power (mega volt ampere reactive). Various electrolytes have been used, including zinc bromide, vanadium bromide, and sodium bromide. The battery is charged as electrical energy from the grid is converted into potential chemical energy. Within the electro-chemical cell, there is a separate compartment for each electrolyte, physically separated by an ion-exchange membrane to allow release of the potential energy to occur. The cycle is a closed loop, so there is no discharge, and the size of the storage is limited by the size of the electrolytic tanks.

3.2.4.2 Batteries

There are a number of battery technologies for storage use on a utility-scale. Lead acid is the dominant battery type, although other batteries—such as sodium sulphur and lithium-ion—are also available. Batteries are electrochemical cells composed of two electrodes separated by an electrolyte. When a battery is discharging, ions from the first electrode (anode) are released into the solution, and oxides are deposited on the second electrode (cathode). To recharge the battery, the electrical charge is reversed, returning the battery to its original condition.

3.2.4.3 Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage systems store energy in the magnetic field created by direct current flowing in a coil of cryogenically cooled superconducting material. Such a system requires a superconducting coil, a cryogenically cooled refrigerator, and a vacuum vessel. It is claimed that these systems are 97–98% efficient and can provide both real and reactive power. Superconducting Magnetic Energy Storage systems can store energy with a loss of only 0.1% per hour, compared to a loss of approximately 1% per hour loss for flywheels. They can recharge in minutes and can repeat the charge/discharge sequence thousands of times without any degradation in the magnet, with recharge time being tailored to meet specific requirements depending on system capacity. Such storage facilities are used to provide grid stability in a distribution system and for maintaining power quality at advanced manufacturing plants.

3.2.4.4 Flywheels

Flywheels store energy by accelerating a rotor to a very high speed and storing this energy in the system as inertia. The rotor must be low weight and allow for the extremely high speeds, so it is manufactured from advanced composite materials. The energy is released from the flywheel by reversing the process to use the motor as a generator, so that the rotor gradually slows down until it is discharged. These flywheels only produce 5–10 kW of power. Size is a consideration because flywheels are often relatively large, and currently do not have very large storage potential.

3.2.4.5 Compressed Air Energy Storage

Compressed Air Energy Storage is a method of storing energy in large quantities of compressed air that is later run through a turbine to generate electricity. Off-peak or low-cost electricity is used to drive a compressor that will force air into an underground storage cavern. When electric power demand peaks during the day, the air is then released from the cavern and run through combustion turbine. The turbine, which requires compressed air to operate, then creates electricity through connection with an electrical generator. For example, a salt cavern can be used to store the compressed air at high pressures (7,600 kilo pascal [kPa]/1100 psi), with a magnitude of up to a day's worth of production depending on plant and cavern size, with a storage efficiency of up to 85% (i.e., on the order of 15% of the energy used in compression is not recovered). Turbines that run off the compressed air vary in size and can exceed 100 MW.

3.2.4.6 Hydrogen

There are concepts in development for the conversion of energy from remote renewables to hydrogen gas via electrolysis of water. This process is about 65% efficient. The hydrogen gas could then be stored before powering fuel cells connected to the remote system. However, the efficiency of this process is a concern, and this technology is still under development.

3.2.5 Summary of Storage Options

Table 13 summarizes the relative cost, size, efficiency, and maturity of the various energy storage options. All of these options are possibilities for assisting in addressing the enhanced ancillary service requirements caused by wind energy, but only the least expensive options will generally be employed. Nickell (2008) suggested that the relative cost and flexibility of the various flexible generation resources, storage, or market mechanisms could be represented as shown in Figure 26. While this figure only shows a qualitative trend, it appropriately suggests that studying the potential of energy storage in conventional hydropower (versus pumped hydropower or other storage technologies) is a good place to start.

Table 13. Approximate capital costs, efficiency, capacity, and level of maturity of various alternative energy storage technologies

	Pumped Storage	Compressed Air	Superconducting Magnetic	Flywheels (high-speed)	Hydrogen
Capital Cost ($/MWh)	7,000	2,000	10,000	25,000,000	15,000
Efficiency	0.8	0.85	0.97	0.93	0.45–0.8
Capacity	22,000 MWh	2,400 MWh	0.8 kWh	750 kWh	0.3 to 2,000 kWh
Maturity	Mature commercial	Commercial	Commercial	New Commercial	Commercial Developing

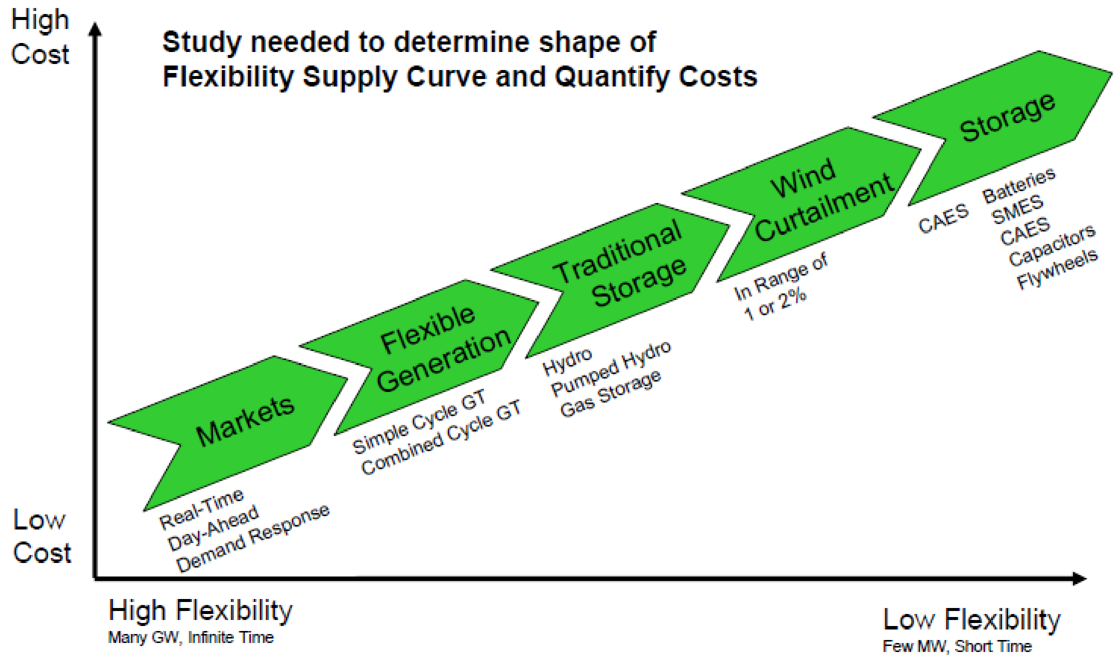

Figure 26. A "Flexibility Supply Curve" that qualitatively compares the various options for provision of ancillary services (Source: Nickell 2008)

3.3 River Systems

One of the characteristics that distinguish hydropower from other generation resources is the widely varying flexibility of the generation units at different hydropower plants, dependent upon the uniqueness of each plant, such as its dam height and reservoir size, river flows, environmental factors, and other priorities. The relationship that exists between hydropower facilities located on the same river system also distinguishes hydropower from other generation resources. The purpose of this section is to describe some of the complexity that exists in this latter relationship, and, in particular, as it pertains to hydro system flexibility and wind/hydropower integration.

Each hydropower plant has distinctive characteristics because the plants are designed on a large group of inputs, sometimes conflicting, that include hydrology, geology, topography, socio/environmental impacts, system constraints, and power demand requirements, all optimized against highest value. In any river system, there can be the choice of developing a few large projects or a larger number of smaller projects. It is usually considered that the optimum system development is to have large storages in the up-stream projects, followed by lower head, but higher flow projects, downstream. This allows more flexible operation of the individual river system, by releasing flows, as required, from the upper storage reservoirs and generating on a run-of-river basis downstream. The flow travel time, and hence distribution with time of energy generation across hydro plants in the system, can be readily modeled and included in system operating rules. In many system-operating models, it is possible to consider the river system as a single, very flexible, generating unit.

In most cases—due to the large capital investment required, the use of public lands, and the long payback period—hydropower plants are typically financed and built by large public utilities or by governments, but not normally by private companies. Depending on the country and its approach through which hydropower has been developed, there is a wide range of possible combinations of hydropower plants. For example, the hydro plants on a given river system may have been built with an overall plan in mind (with respect to power generation) by a single agency—or, one dam at a time, by different organizations with different priorities. In the former case, with one organization owning and operating the dams on a river system, it is very likely that the overall operation of the hydro plants is optimized as suggested above: as one very flexible generating unit. In such an arrangement, given a certain level of required generation, the units can be operated to maximize the power output (per unit of water flow) for the entire system over the course of a day (typically, but possibly some other period of time). Alternatively, for river systems in which there are multiple hydropower owners and operators, if one hydro plant is run to the maximum benefit of its owner without consideration of others, the downstream power plants will likely not be able to run in an optimal sense. For example, some reservoirs may become depleted and forced to operate with lower heads, while others become overfilled, increasing the possibility of spilling water without generating power. Furthermore, depending upon when water is released from the upstream dams, the arrival of stream flows at downstream reservoirs may not be during the peak electricity consumption hours of the day, which could be a problem for run-of-the-river hydropower plants with little storage.

To demonstrate the type and variety of hydropower systems within representative river systems, two example systems are described in the following sections.

3.3.1 Example River System with Multiple Owner/Operators: the Columbia River in the United States and Canada

An example of a complex interaction of hydropower plants along a single river system can be found along the Columbia River system, which runs through southwestern Canada and the Northwestern United States. As shown in Figure 27, there are in excess of 40 hydropower plants in the river system, with multiple owners/operators, split across two countries and four states. With many hydroelectric facilities located along the river, hydro operators realized early on that there were important benefits to coordinating their operation. In 1964, this cooperation was formalized in the form of the Pacific Northwest Coordination Agreement. A main goal of this agreement was to try to optimize benefits of the hydro facilities all along the river by emulating the coordinated operation that could be achieved if operated by a single owner. Priorities of this agreement include producing firm energy based on very low historical stream flows, refilling reservoirs, and producing surplus energy with higher stream flows. Each of these priorities, however, is subservient to meeting Non-Power Constraints, such as those within the Vernita Bar Agreement.[13] This agreement sets flow requirements from the Priest Rapids dam needed for the spawning of fall Chinook salmon in the Columbia River.

[13] For more information about this agreement, see http://www.nwcouncil.org/library/isab/isab98-5.htm.

Figure 27. Map of dams in the Columbia River Basin (Source: U.S. Army Corps of Engineers, www.nwd.usace.army.mil/ps/colbsnmap.htm)

At the head of the mid-Columbia system, the U.S. Bureau of Reclamation operates the Grand Coulee dam and power plant. It is a large storage project (approximately 9,500,000 acre-feet or 11,700 cubic hectometers) with 6,809 MW of nameplate generating capacity. The electricity generated at Grand Coulee is scheduled and marketed by the Bonneville Power Administration, and represents one of its most flexible resources. As indicated in Figure 27, this dam is located upstream of six essentially run-of-the-river dams on the mid-Columbia, whose names, owners/operators, and the nameplate capacities are as follows:

(a) Chief Joseph: U.S. Army Corps of Engineers (USACE), 2,069-MW nameplate

(b) Wells: Douglas County Public Utility District (PUD), 840-MW nameplate

(c) Rocky Reach: Chelan County PUD, 1,287-MW peak

(d) Rock Island: Chelan County PUD, 660-MW peak

(e) Wanapum: Grant County PUD, rated at 1,038 MW

(f) Priest Rapids: Grant County PUD, rated at 955.6 MW

The operation of Grand Coulee significantly influences the operations at these six dams because its flow takes approximately 9.5 hours to travel from Grand Coulee to Priest Rapids (although time varies depending on flow rate). The flow out of Priest Rapids is highly regulated as it flows into an environmentally important region of the Columbia, as prescribed by the Vernita Bar Agreement. For example, Figure 28 shows the discharges from Grand Coulee and Priest Rapids dams during a week in March 2001. The flow output from Grand Coulee is highly variable, whereas the flow output from Priest Rapids is not. During this particular week, there was a non-power flow constraint from Priest Rapids for the protection of incubating salmon.

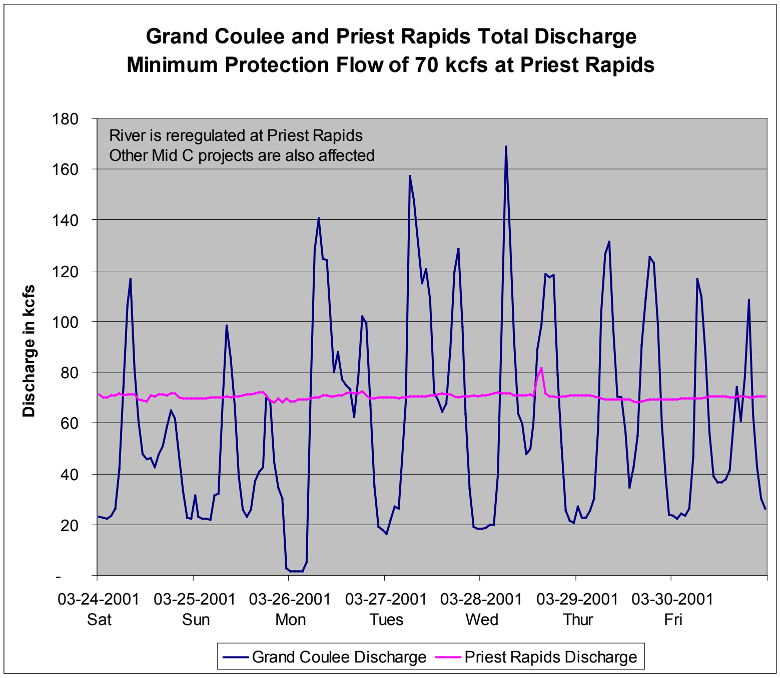

Figure 28. Plot showing the discharge of water from Grand Coulee dam and from Priest Rapids dam during a week in March 2001 (Source: Acker et al. 2006)

Due to the challenges in optimally planning hydro generation amidst multiple constraints and uncertainties, especially in the hourly-to-weekly time frame, the owners of the seven projects on the mid-Columbia from Grand Coulee to Priest Rapids have entered into the Mid-Columbia Hourly Coordination Agreement. The prime objectives of this agreement are to keep the six reservoirs downstream of Grand Coulee full, minimize radical fluctuations in forebay levels, and prevent or minimize unintended spilled water by facilities on the river, therefore focusing on the maximization of power output from the projects. This coordination has been implemented by forming a "Central" dispatch to which the generation requests of each of these projects are submitted. Central receives "uncoordinated" requests every four seconds, then re-dispatches coordinated requests to the Federal Projects at 20-minute intervals, and to the non-Federal projects at 4-second intervals, in an effort to optimize the output of the entire system. In implementing this coordination, all the rights and obligations of each project participant are preserved. Additionally, detailed accounting is conducted, and periodic adjustments made, to ensure that each participant receives its appropriate share of the generating capacity, inflow, and pondage.

As demonstrated through this example of the mid-Columbia dams, there can be a significant amount of complexity and organization required for optimally running the hydropower along a river system. Numerous organizations, agreements, and regulations may be required, resulting in improved overall efficiency or energy production, but may either increase or decrease the flexibility, and create rigid operating agreements that are difficult to modify.

3.3.2 Example River System with a Single Owner/Operator: the Missouri River in the United States

As compared to the Columbia River, a distinctly different river system in the United States is the Missouri River. Along the main stem of this river are six large dams at locations displayed in Figure 29. The hydropower plants located at these dams possess a total generating capacity just below 2,400 MW. All facilities are owned and operated by the U.S. Army Corps of Engineers. The combined water storage capacity in these reservoirs is three times the annual runoff, so there is some flexibility in timing of water releases. Operation of these large dams and hydropower facilities has a dominating effect over the water operations in the entire region. In order to achieve the multi-purpose benefits for which they were created, the six reservoirs are operated as a hydraulically and electrically integrated system. This coordination is accomplished via a Master Manual published by USACE. The Master Manual serves as a guide in meeting the operational objectives of the six reservoirs, and also includes the integrated operation of tributary reservoir water control plans so that an effective plan for flood control and conservation operations exists within the basin USACE (2006).

Figure 29. Figure displaying the Missouri River Basin in the United States and the six large mainstream dams and hydropower facilities (Source: USACE)

As with any federally funded hydropower in the United States, there are multiple uses for these facilities, with power generation being one of the lowest priorities. These dams were created with flood control as their primary purpose, and are also used for navigation, recreation, irrigation, and power generation. Furthermore, there are numerous environmental regulations regarding water releases from the dams pertaining to bird and fish survival. Combined, these priorities and constraints restrict use of the indigenous flexibility available in the hydro generators. Therefore, capacity and energy schedules are set subservient to other priority uses and environmental constraints. While the dams are operated by USACE, the power is marketed and scheduled by WAPA for numerous public power customers. (The power is not available on the Midwest Independent TSO market, but rather is dedicated to certain customers for use in meeting their load). As a result, overlaid on the physical capabilities and constraints of the hydropower facilities are numerous organizations and stakeholders. As described in the Master Manual, WAPA uses the main stem projects as an integral part of the Midwest power grid. "Project

Power Production Orders" that reflect the daily and hourly hydropower limits imposed on project regulation are sent to each project on a daily basis, or more frequently, if necessary. Despite this complexity and the relative infrequency of the interval for setting the hydropower limits, once the capacity and energy schedules are set, there is some flexibility in the use of the hydropower by the recipients of the power, but this flexibility is used by each individual power customer and not for the overall benefit of balancing the electrical system.

3.3.3 Summary of River Systems

The foregoing discussion on river systems should have indicated the complexity and opportunities found in operating multiple hydropower plants in coordination. Unlike flexible thermal power generators, which are primarily "on command" for power generation within their physical operating limits and economic dispatch, there are many additional considerations when dealing with hydropower. While hydro generators themselves may be quite flexible, the availability of their fuel source (water) can be constrained in non-obvious and unique ways, but also in ways that can be understood and used in planning.

Regarding future hydropower generation, there has recently been a major emphasis in North America and Europe on developing small hydro, particularly because in many jurisdictions only small hydro is considered renewable due to the potential impacts of large hydro. Legislation and other measures favoring emerging renewable technology and "green" energy therefore often exclude "large" hydro, since small projects are perceived as having lower impacts. However, the impacts of a single large hydro project must be compared with the cumulative impacts of several small projects yielding the same power and level of service. For example, small projects generally require a greater total reservoir area than a single large project, to provide the same stored water volume. Nevertheless, small hydropower is a necessary and useful complement to the electricity generation mix, particularly in rural areas. The most fundamental determinant of the nature and magnitude of impacts of hydropower projects are the specific site conditions and not the scale of the project. It is also important to optimize development with respect to the complete river system.

3.4 Hydropower Generators and Ancillary Services

The purpose of this section is to describe hydropower generators and their use in power plants in sufficient detail to understand their capabilities and how they can be used for ancillary services and system balancing. Referring to Figure 26, water enters the "penstock" through a grate and flows towards the turbine. Somewhere along the penstock, there is a control valve that permits flow of water to the turbine and is capable of shutting off the flow. Immediately, upstream of the turbine, there is usually a set of "wicket" gates that regulate water flow to the turbine. Turbines are able to respond quickly to changes in demand by varying the flow to the turbines through the wicket gates. For this reason, AGCs are typically installed onto hydro turbines so that they may automatically respond to rapid fluctuations in system load and therefore be used for regulation.

There are three main types of hydropower generators commonly in use today, each capable of achieving efficiencies of 80% to 90%: the Pelton, Francis, and Kaplan turbines. The power output, P, of these turbines is governed by three basic parameters: the flow rate, Q; the head height, h (i.e., the height of the reservoir forebay above the surface of the river immediately downstream of the power house); and the efficiency of the generator, η. Written in equation form:

$$P = Q \times h \times \eta \times (\text{constant})$$

Thus, the power output is directly related to Q and h, and the constant shown in this equation is dependent on the units selected for each parameter (e.g., feet, meters). For any given hydropower plant, the flow rate and head height depend on the hydrological conditions and can vary substantially from year to year. The type of turbine selected for use at a hydropower plant depends on its expected operating conditions. Pelton turbines are employed in situations in which the head is high but the flow rate is relatively low. It is an *impulse* turbine and operates by expanding the high-pressure flow the end of the penstock (see Figure 26) through an efficient nozzle. The high-speed flow exiting this nozzle is directed at specially designed cups extending off a rotor, which receive the flow and redirect it backwards. This process of redirecting the flow causes an exchange of momentum between the flow and the rotor, causing the rotor to spin. Francis and Kaplan turbines are in very wide use worldwide, and unlike Pelton turbines, are *reaction* turbines. Francis turbines can operate efficiently over a broad range of flow rates at medium to high head (20- to 100-meters), whereas Kaplan turbines are used primarily in low head (run-of-the-river) hydro plants. Reaction turbines operate by expanding the high-pressure flow across the blades of the turbine. In doing so, the flow is accelerated over the blades causing a low-pressure region on the blade upper surface, efficiently creating lift and causing the rotor to spin. While this low-pressure region is germane to its operation, it does have one adverse effect: for certain operating conditions, the flow over the blades can *cavitate*. That is, in the low-pressure region, it is possible for the local pressure to drop below the vapor pressure of the water, causing vapor bubbles to form. As the flow exits the low-pressure region of the blade, the vapor bubbles collapse and pit the blade. If run for extended periods of time while cavitation is occurring, the blade surface will erode, reducing its efficiency and potentially leading to failure of the blade and rotor. All reaction turbines have operating conditions that cause cavitation. Another operation condition that occurs in a reaction turbine is that, under certain conditions, a vortex may form in the draft tube causing vibration and damage. Plant operators avoid running turbines in these *rough zones*, as will any automated control systems that may be in place, in order to prolong the turbine useful life. The rough zones can extend across a large range of the turbine operation. For example, on a 110-MW Francis turbine, it would not be unusual for the rough zone to be present for power outputs between 40 MW and 80 MW. Above the rough zone, generator efficiency is about 85% to 90%, whereas below the rough zone it is between 20% and 50%.

Large hydropower plants with large reservoirs are often built with several generators. Having multiple units in such a hydropower plant gives the plant operator flexibility in choosing which units to operate, and the power output level at which to operate them. The same may be true for a run-of-the-river power plant, except during times of the year when the river flows are very high and the plant is running near its full output. Figure 30 shows a plant efficiency curve for two hypothetical hydropower plants with three-generation units each. The efficiency curves are steeper for low flow rates (one unit running) and flatten out as more units are operating. The implication here to wind/hydro integration is that if the *load net wind* (or "*net load*") causes more variations in plant output, the net effect may reduce plant efficiency. Furthermore, if there is also greater uncertainty in the generation required to meet the load net wind, this may cause the system operator to schedule and dispatch the hydro plant at a lower overall efficiency to allow for enough spinning reserve. A reduction in plant efficiency accompanied by an increase in cycling of the units will lead to higher operating costs, which would then show up as "wind integration" cost, as described in the previous chapter. However, the extent to which this may occur and the magnitude of the cost depends on numerous factors and can only be accurately estimated via a comprehensive simulation of the hydro and power system operation.

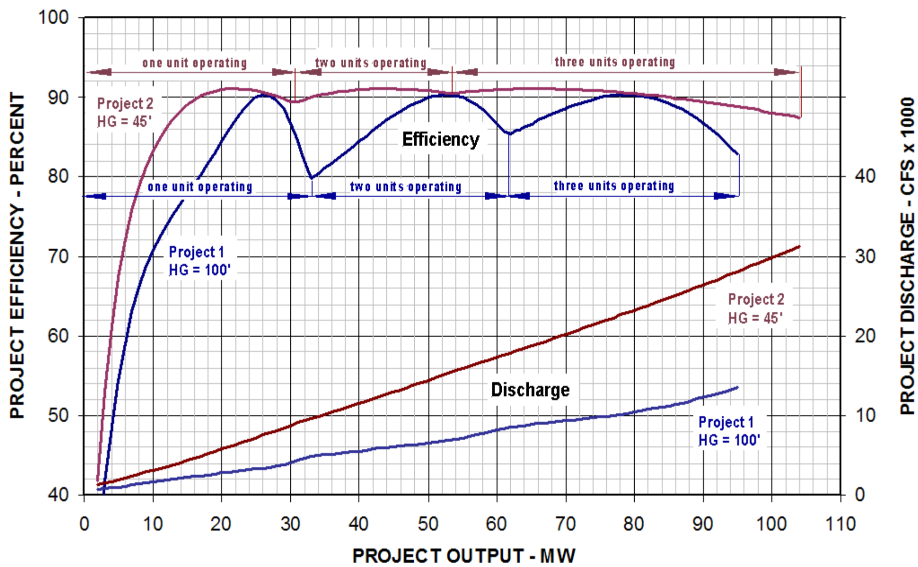

Figure 30. Hypothetical hydropower plant efficiency curves for two different power plants (Source: B. Smith, Oak Ridge National Laboratory)

An example of a large hydropower facility with several generators is the Hoover Dam located on the Colorado River in the Southwestern United States. The Hoover hydropower plant is composed of 17 turbines with a total capacity of 2,074 MW. The dam impounding Lake Mead is tall and therefore a high head is available to the turbines, most of which are the Francis type rated at 130 MW. The capacity factor at the plant is typically on the order of 20% to 30%, depending on hydrological conditions. The effect of flow rate on plant efficiency mentioned above can be seen in a time-series plot of the Hoover plant efficiency for a day in November 2007, shown in Figure 31. Note the plant efficiency is higher when the generation requested is at a higher level.

Due to their flexibility and the low capacity factor of the plant, the generators at Hoover Dam are essentially used for regulation, following the load, and aiding in balancing of the system. Like many hydro generators, they are capable of a very high ramp rate, able to ramp at about 75% of their capacity per minute (~100 MW per minute). Another screen shot of the Hoover Supervisory Control and Data Acquisition is shown in Figure 32. The column on the left-hand side of this figure titled "MODE" shows the state in which each of the generators is being operated. The generation units at Hoover are typically operated in one of four modes, which are described as follows:

1. *Standby (STBY):* The unit is not generating, but available to be brought online. Typically, a unit can be brought online within 5 minutes and generating at full power within 10 minutes (and shut down to full load within 10 minutes).
2. *Automatic Generation Control:* The unit is online and operating on ACG, providing the regulation ancillary service.

3. *Set Point:* The unit is online and running at a set power output entered by the operator (not shown in Figure 32).
4. *Condensing (COND):* The unit is being "motored" and run as a synchronous condenser providing VAR support to the electrical system. In "motoring" a unit, the wicket gates supplying water to a turbine are closed and compressed air is injected into the compartment (draft tube) housing the turbine rotor, suppressing the water of the tailrace (downstream side of the dam) away from the turbine. System power is then supplied to the generator's stator causing it to run as a motor, with the turbine rotor rotating at a speed and frequency that allows the unit to be synchronous to the grid.

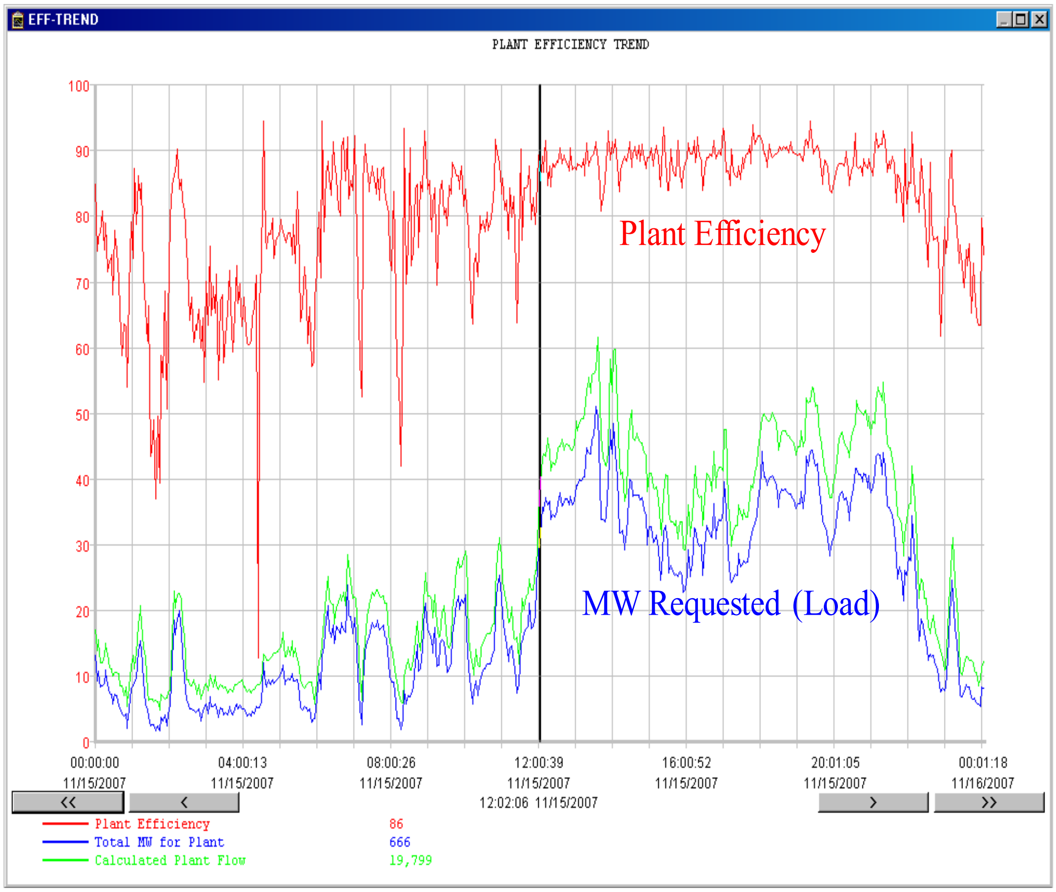

Figure 31. A plot displaying the Hoover power plant efficiency for a typical day of operation, captured by taking a "screen shot" from the Hoover Supervisory Control and Data Acquisition system (Source: U.S. Bureau of Reclamation, Hoover Power Plant)

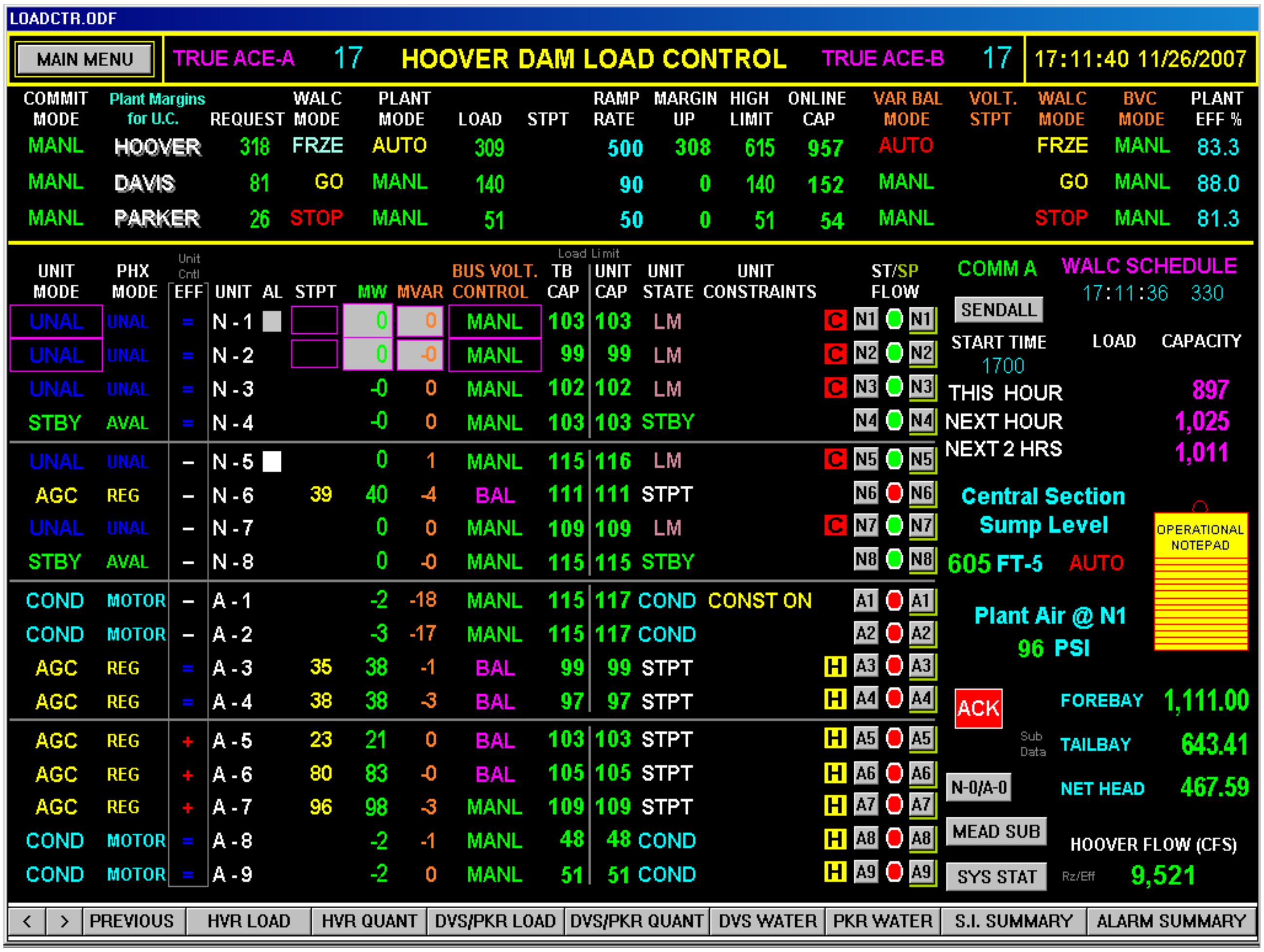

Figure 32. A "screen shot" from the Hoover power plant Supervisory Control and Data Acquisition system, showing numerous parameters concerning unit operation (Source: U.S. Bureau of Reclamation, Hoover Power Plant)

In addition to these four modes, a unit may also be listed as unavailable (UNAL); for example, if it is out of service for maintenance. Figure 32 shows the hour's capacity schedule was 897 MW, the actual generation was 318 MW, and the online capacity was 957 MW. Since the online capacity was significantly more than the actual generation, the balance (639 MW) represents capacity available as spinning reserve. A typical power production pattern for Hoover power plant is shown in Figure 33. As demonstrated in this figure, although the units online at any given moment at Hoover may be operated to maximize their collective efficiency, the overall operating strategy is not to produce the most energy or peak efficiency, but rather to utilize the hydropower for the more valuable ancillary services of regulation, load following, and reserves (spinning and non-spinning). The Hoover power plant is an example of a very flexible plant, within it constraints, and the downstream plants from Hoover are used to re-regulate the flow on the river and therefore offer much less flexibility in their operation. Indeed, it is because of these downstream facilities that Hoover can be run as it is.

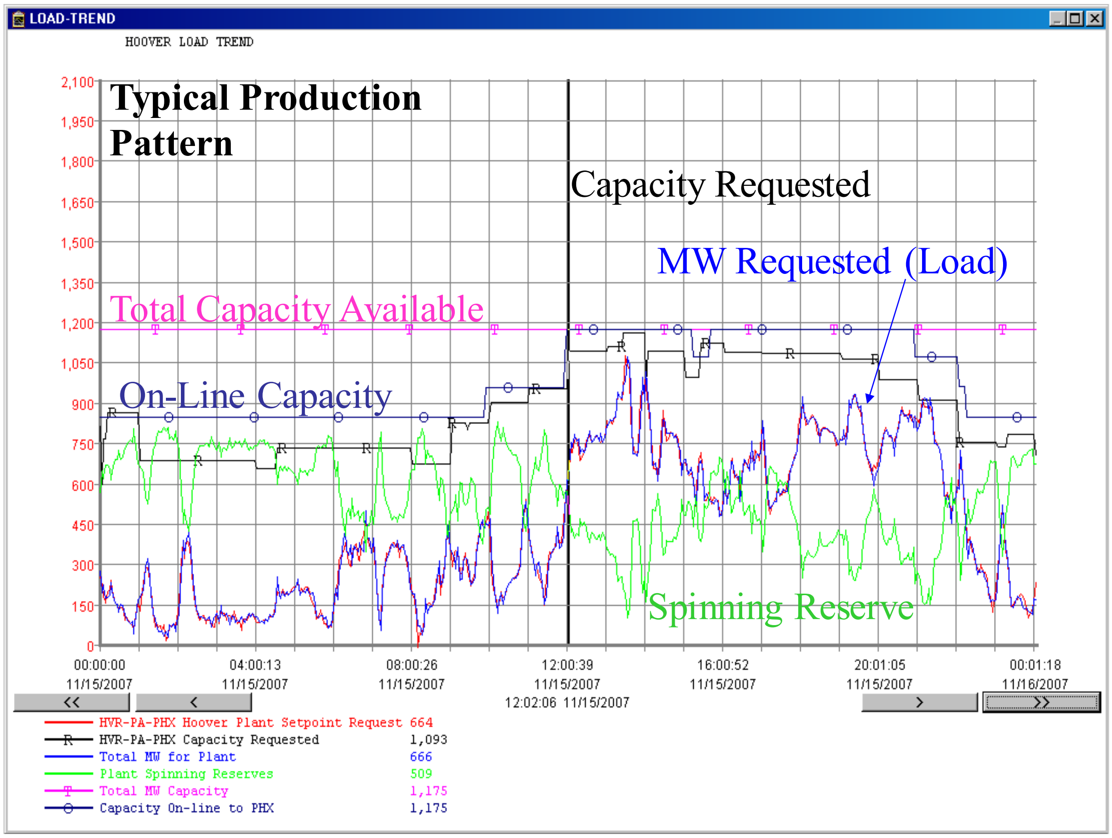

Figure 33. A typical production pattern from generators at the Hoover power plant during a day in November 2007 (Source: U.S. Bureau of Reclamation, Hoover Power Plant)

As demonstrated in the example of the Hoover power plant, hydropower can provide unique benefits to an electrical system. First, when stored in the reservoir behind a dam, it is available for use when required. Second, the energy source can be rapidly adjusted to meet demand instantaneously. These benefits are known as ancillary services described in Chapter 1 of this report, and they include the following:

1. *Spinning Reserve:* The ability to run at a zero load while synchronized to the electric system; when loads increase, additional power can be loaded rapidly into the system to meet demand
2. *Non-Spinning Reserve:* The ability to enter load into an electrical system from a source not online—while other energy sources can also provide non-spinning reserve, hydropower's quick start capability is unparalleled, taking just a few minutes, compared with as much as 30 minutes for other turbines and hours for steam generation
3. *Regulation and Frequency Response:* The ability to meet moment-to-moment fluctuations in system power requirements; hydropower's fast response characteristic makes it especially valuable in providing regulation and frequency response
4. *Voltage Support:* The ability to control reactive power, thereby assuring that power will flow from generation to load
5. *Black Start Capability:* The ability to start generation without an outside source of power, which allows system operators to provide auxiliary power to more complex generation

sources that could take hours or even days to restart (systems having available hydroelectric generation are able to restore service more rapidly than those dependent solely on thermal generation)

3.5 Multi-Purpose Hydro Facilities

In addition to offering clean, renewable energy, hydropower is often only one of a number of benefits of a multipurpose water resources development project. Hydropower is generally integrated within multipurpose development schemes and can therefore subsidize other vital functions of a project. Typically, construction of a dam and its associated reservoir results in a number of benefits associated with human well-being, such as secure water supply; irrigation for food production and flood control; and societal benefits, such as increased recreational opportunities, improved navigation, the development of fisheries, cottage industries, etc. This is not the case for any other source of energy.

When considering the integration of hydropower with other renewable energy, like wind power, it is important to recognize that hydropower flows are subject to the many constraints on operations, including minimum/maximum flows and minimum/maximum ramp rates. Allowable flows are dictated by multivariate optimization considering the following variables:

1. Flood control and safety of structure
2. Fish, wildlife, and other related environmental needs
3. Irrigation
4. Navigation
5. Recreation
6. Energy/power demands

Often, power needs are not high in priority, and energy delivery must fit into constraints imposed by the needs of other systems. Certainly, while the many priorities of a hydro development often enable the construction and use of hydropower, they also constrain the flexibility of its use at a macro level (e.g., set daily, weekly, or monthly flow requirements, discharge rates, lake levels). These constraints depend on the river system and specific hydropower facility, and can vary greatly from one hydropower plant to another. Indeed, this is one of the primary reasons it is difficult to generalize the results of wind/hydro integration in one system and apply them to another, and one of the reasons research Task 24 was formulated.

3.6 Institutional, Organizational, and Legal Issues Related to Hydropower

The ability to schedule and use the flexibility of a hydropower plant ultimately depends on the priorities of the hydropower facility and the organizations that have authority over its operations. Due to the multipurpose nature of many hydropower plants and the relationship between hydro facilities on a river system, there can be many organizations, agreements, regulations, and laws that govern the system. Just as the river systems and priorities of hydropower plants vary, so do the organizational and legal frameworks within which they operate. It is this variation that differentiates one hydropower system from another, establishing its operating flexibility, and distinguishing it from the thermal power resources that can be used for system balancing and ancillary services. In the section that follows, an example is provided of the organizational and legal complexity that can surround a hydropower project and define its flexibility for use in wind/hydropower integration. It should be noted that this complexity is not necessarily common, but that it can and does occur in highly regulated systems.

3.6.1 Example of a Organizational and Legal Complexity: The Colorado River System in the United States

As an example of the organizational and legal complexity that can surround the operation of a hydropower plant, essentially defining the flexibility of the generation, consider the Hoover Dam and the power plant on the Colorado River in the arid Southwestern United States (see Figure 34). The drainage basin is broken into a two parts: the Upper Basin and the Lower Basin, with the division between the two located at Lees Ferry, just downstream of Glen Canyon Dam at the head of Lake Powell. Hoover Dam is in the Lower Colorado Basin and impounds Lake Mead, a large storage reservoir. The large storage reservoirs along the river can hold up to four times the annual average runoff, and serve the important role of delivering water to municipalities and agricultural customers throughout the Southwest, assuring water supplies through extended drought periods.

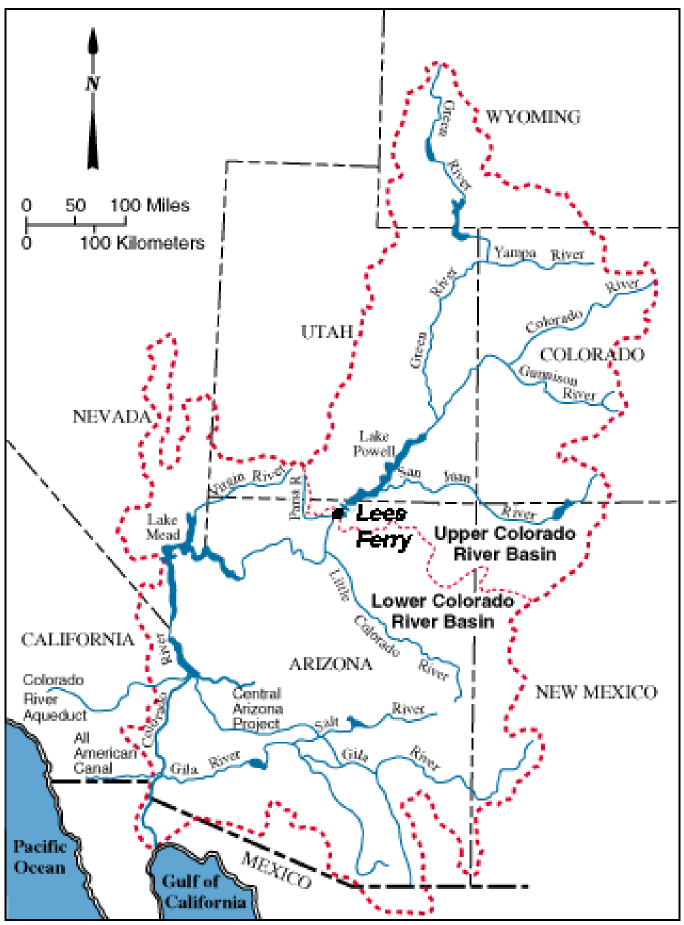

Figure 34. Illustration of the upper and lower drainage basins of the Colorado River (Source: U.S. Bureau of Reclamation)

The U.S. Bureau of Reclamation (Reclamation) has been authorized by legislation to construct facilities and produce electric power at Hoover Dam, Glen Canyon Dam, and other smaller facilities along the Colorado River. While Reclamation is the Federal agency responsible for water operations and power production at the major dams along the river, WAPA is the Federal agency designated to market and deliver this power. WAPA enters into electric service contracts on behalf of the United States with 15 public and private utility systems for distribution of hydroelectric power produced at Reclamation facilities in excess of project demand. These agreements are long-term bilateral agreements in which a power customer receives an allocation of the Hoover power and energy, which the customer may not re-market.

Reclamation is part of the U.S. Department of the Interior, and the Secretary of the Department is vested with the responsibility to manage the mainstream waters of the Lower Basin pursuant to applicable Federal law. The responsibility is carried out consistent with a body of documents referred to as the Law of the River.[14] The Law of the River comprises numerous operating criteria, regulations, and administrative decisions included in Federal and State statutes, interstate compacts, court decisions and decrees, an international treaty, and contracts.

The following are particularly notable among these documents:

1. The Colorado River Compact of 1922, which apportioned beneficial consumptive use of water between the Upper Basin and Lower Basin
2. The Boulder Canyon Project Act of 1928, which authorized construction of Hoover Dam and the All-American Canal, required that water users in the Lower Basin have a contract with the Secretary, and established the responsibilities of the Secretary to direct, manage, and coordinate the operation of Colorado River dams and related works in the Lower Basin
3. The California Seven Party Water Agreement of 1931, which, through regulations adopted by the Secretary, established the relative priorities of rights among major users of Colorado River water in California
4. The 1944 Treaty with Mexico (and subsequent minutes of the International Boundary and Water Commission) related to the quantity and quality of Colorado River water delivered to Mexico
5. The Upper Colorado River Basin Compact of 1948, which apportioned the Upper Basin water supply among the Upper Basin states
6. The Colorado River Storage Project Act of 1956, which authorized a comprehensive water development plan for the Upper Basin that included the construction of Glen Canyon Dam and other facilities
7. The 1963 United States Supreme Court Decision in *Arizona v. California*, which confirmed that the apportionment of the Lower Basin tributaries was reserved for the exclusive use of the states in which the tributaries are located; confirmed the Lower Basin mainstream apportionments of 4.4 million acre-feet of water for use in California, 2.8 million acre-feet for use in Arizona, and 0.3 million acre-feet for use in Nevada; provided water for Indian reservations and other federal reservations in California, Arizona, and

[14] Underwood, D. B., *The Law of the River: A Primer,* The Metropolitan Water District of Southern California, CLE International.

Nevada; and confirmed the significant role of the Secretary in managing the mainstream Colorado River within the Lower Basin

8. The 1964 United States Supreme Court Decree in *Arizona v. California*, which implemented the Court's 1963 decision; the Decree was supplemented over time after its adoption and the Supreme Court entered a Consolidated Decree in 2006 that incorporates all applicable provisions of the earlier-issued Decrees
9. The Colorado River Basin Project Act of 1968, which authorized construction of a number of water development projects including the Central Arizona Project and required the Secretary to develop the Long-Range Operating Criteria and issue an Annual Operating Plan for mainstream reservoirs
10. The Colorado River Basin Salinity Control Act of 1974, which authorized a number of salinity control projects and provided a framework to improve and meet salinity standards for the Colorado River in the United States and Mexico; and the Grand Canyon Protection Act of 1992, which addressed the protection of resources in Grand Canyon National Park, consistent with applicable Federal law
11. Among other provisions of applicable Federal law, the National Environmental Policy Act and the Endangered Species Act of 1973, as amended, provide a statutory overlay on certain actions taken by the Secretary

With well in excess of 50 laws, acts, or other relevant documents, the Colorado River is highly regulated. Furthermore, there are many organizations and regulatory agencies that have a stake in how the river is managed. Much of this Law of the River is pertinent to power generation and the flexibility of its use, though often indirectly. Indeed, if one were to prioritize the functions performed by Hoover Dam, it could be ordered as follows:

1. Flood control / protection of the structure
2. Compliance with environmental regulations and laws
3. Downstream water deliveries
4. Recreation (reservoir water levels downstream of Hoover)
5. Power generation

As is evident, the highest priorities of the dams along the Colorado River system pertain to water management, and there are numerous organizations and stakeholders involved in operation of the system. With respect to power generation at Hoover Dam, the constraints imposed by its higher priority functions result in an allocation of power and energy to Hoover power customers on a monthly basis. The power allocation is based on the available head and is typically some fixed percentage of the plant capacity, whereas the energy allocation is derived from the expected water deliveries from the dam. These allocations are projected approximately 6 months before the beginning of the year, and are updated as the year progresses and the actual hydrological conditions become known. Due to the many laws and regulations, there is no ability to shift usage of the water deliveries from one month to the next for purposes related to power generation, and it is necessary that customers use their power allocations within constraints dictated by the law. Within each month, however, there is significant flexibility in scheduling and use of generators, as was demonstrated in figures in the previous section. Fortunately, the law is implemented in such a way that the flexibility of and constraints on power generation are fairly clearly delineated and conveyed to power customers. Furthermore, the two dams downstream of Hoover Dam (Davis and Parker dams) are operated to re-regulate the flow out of Hoover and to water deliveries, thus facilitating the flexibility at Hoover.

3.6.2 Summary

Once the higher priority functions of a hydro facility or system are satisfied, planning of the hydropower can take place, using whatever remaining flexibility is available for use. Authority, priority, and markets drive the scheduling of power in an optimized hydro system. Examples of ways hydropower systems operate include: operation in an integrated system, where a central utility has responsibility to meet electric load growth; or, operation in a more run-of-the river mode, with little seasonal or yearly storage capability, governed more by hydropower capacity, rather than energy (i.e., more water available than generators to run it through). For cases in which a utility may not have load growth responsibility, but owners purchase supplementary power for wholesale customers if they request assistance, all additional costs are passed directly on to those wholesale customers in near real time. Power may be allocated on a project-by-project basis (rather than system basis) in locations where there is the ability to store water over long periods, and output is more energy-limited than capacity-limited.

Individual institutional situations are important as the context for assessing wind/hydropower integration opportunities. For example, in some cases, an individual hydropower resource may be developed for the benefit of specific customers, whereas in other cases, a whole drainage basin may be operated in an integrated fashion.

Politically, hydropower and other water use allocations are often contentious. Some parties may wish to use existing hydropower allocations to support integration of wind energy, where there is interest in wind energy development for economic development or other reasons. Other entities may see wind energy as a threat to their interests; for example, many utilities with Federal hydropower allocations also have large investments in fuel production and other electric generating stations, which could potentially be displaced by wind energy generation. With numerous potential stakeholders often with opposing objectives, it can be very difficult to modify the operating criteria of a given hydro facility and its power plant. Institutional factors hinge mainly on the type of control and responsibility held by a hydropower utility or operating agency.

This work concludes that using hydropower to address added ancillary service needs in an electrical system with wind power should take account of the flexibility of the hydropower in the system. This is because of the complex and often convoluted nature of setting hydro system priorities and operating plans. In other words, even amidst the many constraints and multiple objectives that may be placed on hydropower generation, there is often a significant amount of operational flexibility that still remains. Therefore, the purpose of the many and varied case studies that contributed to Task 24 was to consider wind and hydropower integration within a system using existing hydropower flexibility. That said, it is not outside the realm of possibility to consider modifying hydropower operational criteria or constraints for the benefit of the system; however, Task 24 primarily investigates using the existing flexibility of hydro resources, as this is perceived to be considerable.

3.7 Variability and Uncertainties of Hydro Resource Across Time Frames of Importance in Balancing Area Operation

A focus of this report has been to discuss the variability and uncertainty in *load net wind*, which is the effective load signal that must be balanced with generation while maintaining transmission system reliability. In balancing the system, planners and operators attempt to economically optimize system operation, given certain constraints, and amidst uncertainties in load, generation availability, wind power, market prices, etc. Understanding the uncertainties and having a good sense for the variability in load net wind will aid in managing the resources most effectively. Alongside the load net wind, hydropower also has variability and uncertainty related to its production, but across different time scales than wind energy. For the time scales of interest to system operation and planning, the variability and uncertainty of hydropower is described as follows:

Regulation (seconds to 10 minutes):

- There is no uncertainty in hydropower generation (beyond unexpected outages) or variability in the hydropower resource on these time scales.
- Hydropower units are typically very agile and responsive to load (or load net wind) fluctuations in this time frame. Hydro generators are generally outfitted with AGC and are used to keep the system frequency and tie line flows within desired levels. Hydro generators also participate in low voltage ride through and VAR support.

Load following (tens of minutes to a few hours):

- There is typically very little uncertainty in hydropower generation or variability of the inflows over this time frame. However, uncertainty can be introduced through the flow releases at upstream dams in river systems with multiple hydropower facilities.
- Though sometimes constrained due its higher priority functions (limiting flow rates, ramp rates, or reservoir levels), hydropower can typically be employed to follow the trends in load or load net wind. Generally, the larger the storage reservoir, the greater the ability to follow load over longer time periods.
- Hour-ahead forecasting and plant-active power management and scheduling are used.

Scheduling and Unit Commitment (hours to several days):

- Scheduling and unit commitment aims to optimize the mix of generating units to supply the hour-by-hour forecasted load at minimum cost (additional reserve units are also optimally scheduled).
- Good day-ahead and multi-day forecasting of load (or load net wind) and hydropower is key.
- Hydropower plants, especially those with less water storage (on the order of days to hours or less), experience uncertainty over this time frame. This can be due to difficulty in predicting inflow due to precipitation, or due to interactions on a river system with multiple dams. As an example of the latter, refer to Figure 35, which shows a plot of the day-ahead flow estimates issued by USACE for Chief Joseph Dam for each day in

January 2004. The dark blue line represents the final day-ahead estimate issued by USACE, and the thin red line is the actual discharge for that day. The deviation between the day-ahead estimated flow and the actual flow is shown by the light green line, which refers to the scale on the right-hand side of the plot. Note the percent deviation between the estimated flow and reconstructed flow varies between roughly +40% and -15%. This significant deviation can be problematic for the system operator of any hydropower plants located downstream that rely on this forecast.

- As for the runoff and inflow, these do vary over this time scale. For hydro plants with little or no storage, and not embedded in a cascade of hydro dams, this variation can be significant. Otherwise, shorter-term inflow fluctuations greatly impact hydro generation. The power output of most hydropower plants varies significantly over this time frame; however, that variation is typically planned and is in response to market conditions or demand, and sometimes other non-power requirements. Therefore, on the order of hours to several days, there is little unplanned variation in hydropower production.

Resource and Capacity Planning (several weeks to years):

- In the time frame of several weeks, hydropower can be very predictable, especially if large reservoirs are present in the system. Without large storage reservoirs, the energy available can still be reasonably predictable, but depends on the weather, precipitation, and overall hydrological conditions. As the planning time frame transitions ahead to a year, the uncertainty in hydropower can increase significantly. Hydro systems are typically planned a year ahead to a few years ahead by considering many different future scenarios for the precipitation. It is common for the year-ahead, firm capacity of a hydropower plant to be set based on some historical years of very low inflows, combined with what is predicted for the next year based on the current climatologically information.

In longer time scales covering months to years, hydropower exhibits unplanned variations and significant uncertainties. Figure 36 shows an example of the significant inter-annual variations that occur in hydropower systems. This figure shows the annual volume of runoff in the Colorado River in the Southwest United States plotted over a 100-year period. As seen, there are quite significant variations (+/– 50% of the mean flow volume) and the mean flow volume itself seems to be changing. As an example of the relative variability of wind and hydropower over short and long time scales, Westrick et al. (2003) presented the data shown in Figure 37. The plot on the left side of this figure displays the intra-daily volatility as a fraction of plant capacity at a hypothetical 100-MW wind power plant at Goodnoe, Washington, U.S., versus the volatility of inflow to the 460-MW Ross hydropower facility on the Skagit River, also in Washington (based upon a 22-year data record). Obviously, the daily volatility of wind power is quite significant compared to the inflow. The right side of Figure 37 shows a plot of the average capacity of the wind and hydro plants at these same two locations from May through September, the peak months for power demand, over the 22-year data record. Over the time scale of many years, the wind power capacity varies about 15%, while the river inflow varies by about 40%. While these are only two examples, this type of variation in inflow is common in hydropower systems worldwide. The volume of flow that travels down a river annually is related to the amount of electrical energy that can be produced. River systems with run-of-the-river type plants will be subject to these large variations. Alternatively, large variations in energy produced by hydropower plants can be somewhat mitigated by building one or more large reservoirs within a river system, capable of holding in excess of 1 year's runoff. In such a river system, there will still be variations; however, they are more to the integral of the annual runoff over 1 or more years (depending on the amount of water storage) rather than the yearly precipitation.

The capacity value of a hydro plant (or any power plant) is based on a reliability metric such as ELCC, and is indicative of the generating capacity that system planners can count on having available during the peak periods of the year. Hydropower plants can have capacity values on the order of 50% to 95%, and the value at any given hydro plant may vary considerably over a period of several years due to the variations in annual precipitation, reservoir levels, etc.

Some hydropower plants with reservoirs that can store multiple days (minimum) to multiple years of annual runoff can potentially create new "products" for electricity customers that essentially repackage wind power into the shape of a more traditional "flat block" purchase. These products are often referred to as *storage and shaping products*. A typical wind *storage* product refers to taking wind power into a hydropower system as it comes, then redelivering it at some later date (next day, week, month, etc.). The *shaping* product refers to delivering a flat block of firm energy that is equal in energy content to the actual wind power production. Bonneville Power Administration in the United States has offered a product like this in the past, and Hydro-Québec and Manitoba Hydro have considered creating similar products.

As is evident from this discussion, the variability of hydropower and uncertainties in forecasting its production occur primarily over the longer time scales. As a mature technology, these factors have been long accounted for in system planning and operation. It is likely that the availability of wind energy, which from year to year is less variable than hydropower, may be a complementary system energy resource. When considering system flexibility, the ability of hydropower to provide regulation, load-following, reserves, and energy storage services will depend on annual changes in precipitation. Generally speaking, there will be less flexibility in drought years and in flood years, and more flexibility during "normal" years.

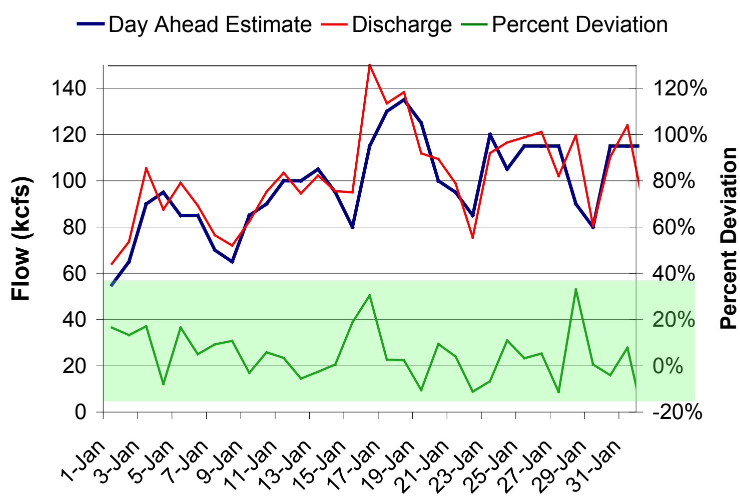

Figure 35. Day-ahead flow estimates versus actual flow from the Chief Joseph Dam in Washington, U.S., provided by USACE, for the month of January 2004 (Source: Grant County Public Utility District)

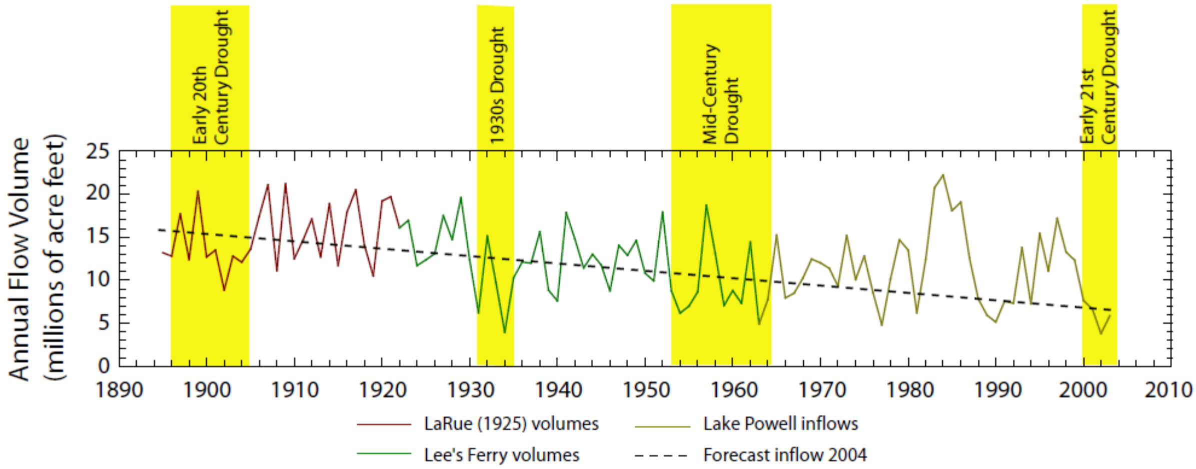

Figure 36. A time-series plot of the annual flow measured on the Colorado River in the Southwestern United States, demonstrating annual and long-term variability (Source: USGS 2004)

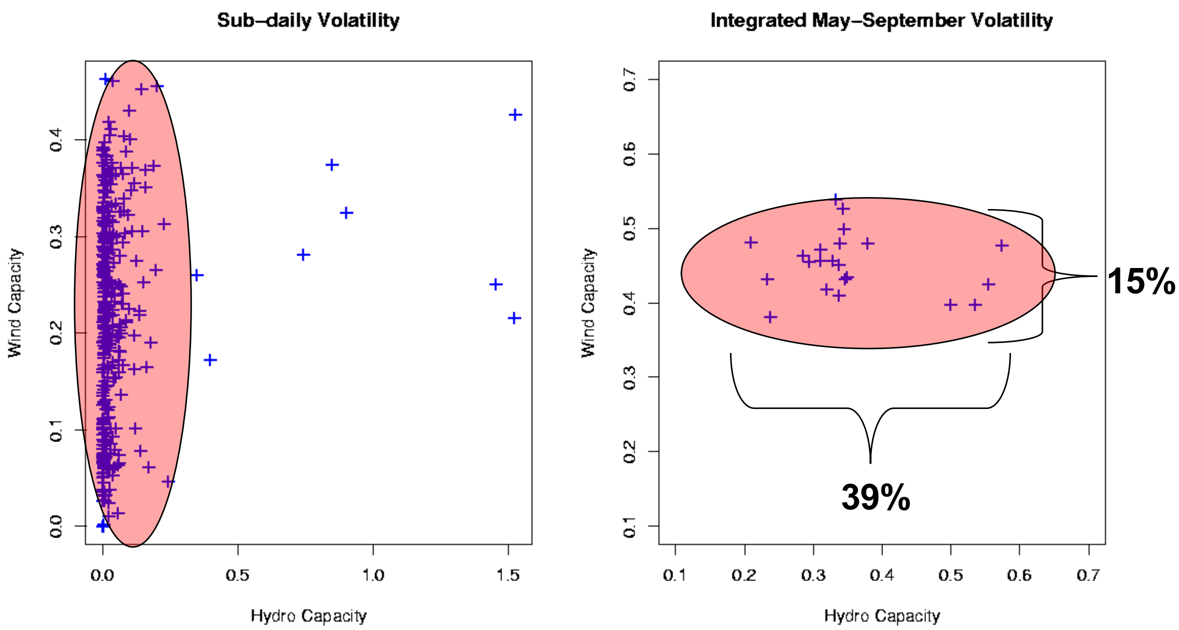

Figure 37. The intra-daily volatility of inflow to the Ross hydropower facility and the hypothetical power output from a wind power plant at Goodnoe (left), both located in Washington, U.S.; and, the average operating capacity from May to September for the same two power plants (right) (Source: Westrick et al. 2003)

A broad perspective of the time horizons of interest in a hydro system is shown in Figure 38. As displayed, the wind variability crosses several time frames of importance. Whether or not wind energy will actually impact any of the issues related to hydro impoundment (blue bars) or biological communities (green bars) issues is not obvious. However, wind variability and uncertainty will affect the hydropower issues (yellow bars) with time frames less than a year and especially those less than a week. For example, an unexpected increase in wind output during any given hour (outside the normal bound of the wind forecast error) could affect short-term water deliveries if hydro production is decreased to compensate. It is the nature of these types of interactions between the wind and the hydro that is the subject of Task 24.

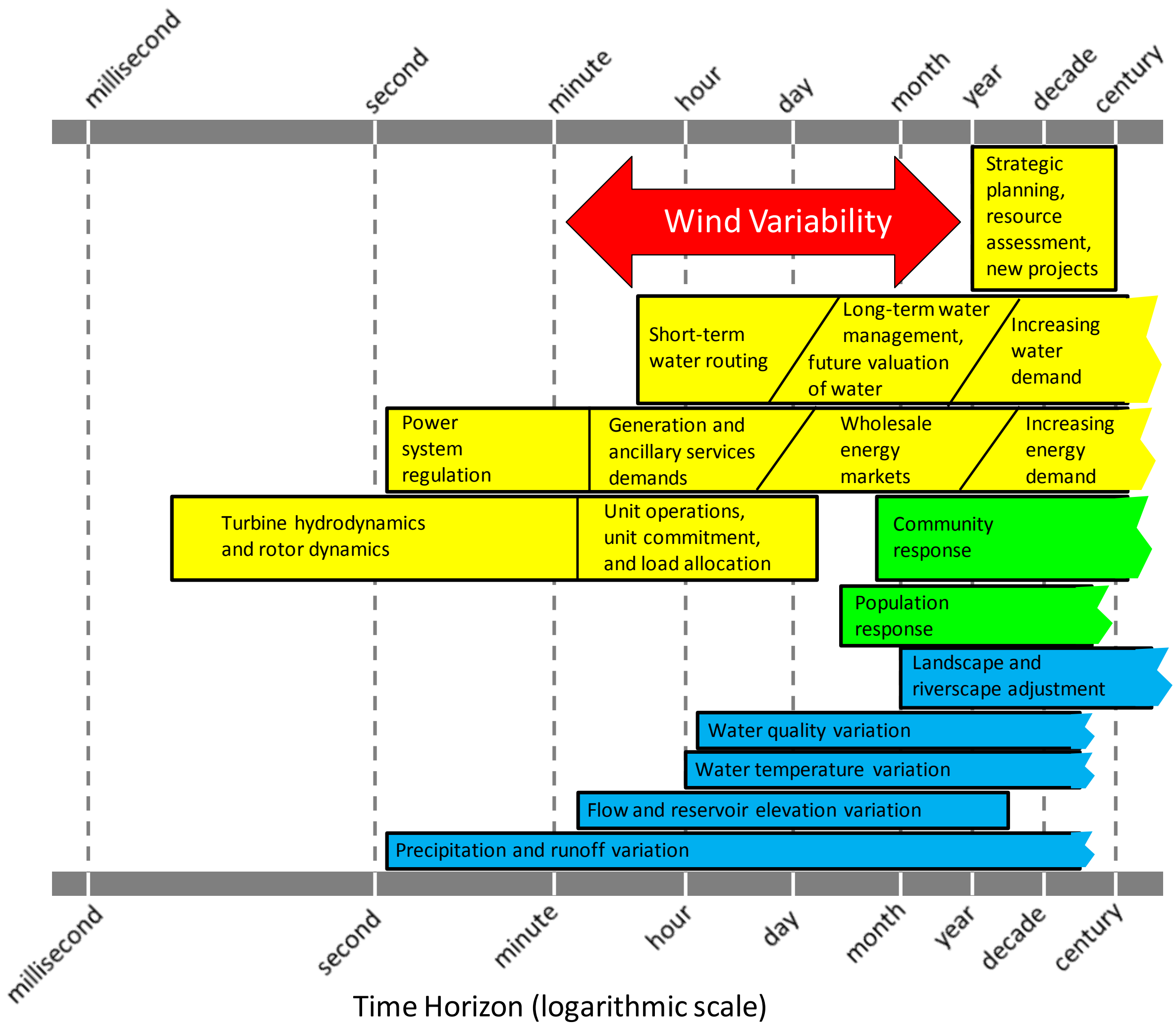

Figure 38. Time horizons of relevance in the hydro system with respect to the hydro impoundment (blue), biological communities (green), hydropower (yellow), related to the time scales of wind power variability (Source: Oak Ridge National Laboratory)

3.8 Planning of the Hydro System

Due to the variability of hydropower on the longer time scales, it is necessary for long-term planning to ensure sufficient generation is available to meet the load in the months and years ahead, especially in drought years. For river systems with numerous power plants and reservoirs, there is a need for coordinated planning of the resource. As such, it is common for hydropower operators and utilities to participate in joint planning processes and agreements. These planning processes will set an overall plan for water operations on the river, complying with any environmental requirements and meeting the priority functions of the major dams on the river. Results from long-term planning operations may be, for example, a yearly plan of target reservoir elevations on a monthly basis for the large storage reservoirs in a system, planning for a possible recurrence of a critical period of historically low stream flows as well as for the flows that are actually anticipated based upon best forecasting. Within this broader plan, a more detailed plan for operating the hydropower is created, attempting to optimize use of the resources available. Utilities or TSOs can then craft their yearly plans for generation. As the year progresses and actual hydrology differs from expected hydrology, adjustments are made to the plan as well as to the amount of water to be delivered downstream. This allows for updating the resource and operation plan, allocating excess or securing additional generation resources in the monthly-to-annual time frame. These adjustments ensure a balanced load and resource portfolio under changing river conditions and needs.

3.9 Social and Environmental Impacts

Any infrastructure development inevitably involves a certain degree of change. The construction of a dam and power plant, along with the impounding of a reservoir, creates certain social and physical changes. Difficult ethical issues, such as ensuring the rights of nations to develop, and ensuring that the rights of people and communities affected by a project are respected, are also likely to arise. The critical action is to explore and anticipate all social and environmental impacts early in the planning process so appropriate steps can be taken to avoid, mitigate, or compensate for impacts.

Hydropower has a long history, and lessons have been progressively learned. It is clear that many hydro plants in the world have had significant environmental impacts. Today, the profession is well aware of the problems to be addressed, and the expertise exists to mitigate the known impacts to achieve an acceptable balance—and research is continuing. Reservoirs can in fact focus attention on existing problems in a watershed.

It would be virtually impossible today for a hydro plant of significant size to move ahead without detailed studies on its potential impacts being conducted, and a comprehensive report of environmental impacts being prepared, including relicensing of existing hydro plants. However, the framework, criteria, and degree of public involvement varies from country to country. These impact assessments will be an integral part of a multidisciplinary planning approach, and include a strong element of public consultation. Environmental Impact Assessments should cover positive and negative impacts, both upstream and downstream of a proposed project. These impact assessments often also apply to the relicensing of old hydropower facilities.

Once in place, hydropower has a significant positive impact on electrical system operation, providing carbon-free energy at low cost, price stability, and flexible generation resources. These positive impacts may grow in the future, as hydropower is deployed to enable wind integration.

3.10 Summary: Hydropower as a Balancing Resource and Energy Storage

The material presented in this chapter describes the salient aspects of hydropower generation that are relevant to wind and hydropower generation. The type and magnitude of ancillary services and reserves that can be provided by a hydropower plant depend on whether it possesses significant storage or if it is a run-of-the-river plant with limited storage. The flexibility of operation also depends on whether or not the hydropower is part of a cascade of dams on a river system, and the level of coordination between those on the same river. A summary of the various types of hydropower plants and their associated ability to provide ancillary services is given in Table 14.

Hydro facilities often have numerous functions—power generations being one—that guide their operation and define their flexibility. Layered on top of the physical and functional planning, there may be numerous organizations and stakeholders involved, along with differing market or economic situations. It is the interaction of the many functions, system configurations, and stakeholders that establish the authority, priority, and economics that govern the potential for wind and hydro integration.

Thermal power resources are also used for system balancing. Some of those resources, such as coal-fired steam power plants, are slowly varying with slowly varying marginal prices. Others, such as simple cycle gas turbines, can vary rapidly but also have rapidly varying marginal prices that can often be hard to predict. Thermal plants typically are more costly to operate than hydropower, and therein lies the main reason and main opportunity for considering hydropower as a primary balancing resource in systems that incorporate wind power.

Table 14. Summary of hydro plant storage characteristics and potential for use in provision of ancillary services and system balancing

Hydro plant Storage Characteristics	Description	Flexibility for System Balancing and Ancillary Services
Run-of-the-River (no storage)	Very small hydro plant, mostly domestic or farm level, irrigation canals	Very Little
Hydro with “regulating” storage (1–5 hours)	Typically small hydro plant, but can have significant generation if flow in river is large	Limited potential to handle deviations due to forecast errors; regulation and load following possible
Hydro with “daily” storage (5 hours – 2 days)	Small-to-medium capacity hydro projects that may be integrated, or in island grids	Useful for load following and regulation; can cover some deviations due to forecast errors; reserves
Hydro with “weeks” storage (2 days – 2 weeks)	Medium hydro, but could be large hydro with high head and small head pond, or part of a large hydro cascade	Effective for regulation, load following, and reserves; short-term storage and shaping products possible
Hydro with “annual” storage (2 weeks – 3 months)	Medium-to-large hydro	Good potential for provision of ancillary services and reserves; flexible operation; storage and shaping products possible
Hydro with “multi-year” storage (3 months to multiple years)	Large hydro	Excellent potential for provision of ancillary services and reserves; very flexible operation; storage and shaping products possible
Pumped storage	Small-to-large hydro	Good potential provision of ancillary services and reserves; storage and shaping possible if a large reservoir

The overarching question for studying wind and hydropower integration is whether system-operating impacts due to wind power can be accommodated by hydropower within the constraints currently in place on hydropower (or not easily changed), and in an economically advantageous way. And if so, what changes will this cause to hydropower operations or costs? In concept, hydropower should be able to provide short- to medium-term buffering of the enhanced variability and uncertainty wind power induces in the overall load net wind. Adding wind power to the system may or may not help hydropower meet power and other system demands, and the influence on other hydro functions, such as water deliveries, must be considered. That said, even within the constraints currently imposed on hydropower, it is a valuable system balancing resource, and possesses the inherent qualities needed to facilitate wind integration. The case studies performed as part of Task 24 were intended to provide some insights into wind and hydro integration, demonstrating the level of its feasibility for a variety of different hydro, wind, and electrical system configurations.

4 Power System Planning and Operation in Systems with Wind and Hydropower

4.1 Introduction

Chapter 1 of this report introduced the aspects of electric system operation and planning that are of most relevance to wind integration: utilities and markets, ancillary services, and system planning and operation. It provided the vital background necessary to understand the reasons for forming Task 24, described the objectives and questions being addressed, and presented the members and work plan of the task. Chapters 2 and 3 went on to provide descriptions of wind power and hydropower, respectively, discussing the aspects of importance to the Task 24 objectives and expected results. Chapter 2 presented a perspective on the value of wind energy, and then described in detail the characteristics of wind power variability and uncertainty, their relationship to power system operation and planning, and wind power's contribution to system capacity. Chapter 3 provided an overview of hydropower, and then discussed in detail aspects of hydro system operation and planning relevant to electrical system operation and planning. Of particular importance were aspects of hydropower of importance to wind integration. The chapter concluded with a summary of issues related to hydropower as a balancing resource and for energy storage. The material presented suggests that systems with hydropower may be well suited to incorporate wind power, due to the potential for synergistic operation of wind and hydropower facilities within or across balancing areas. However, though inherently flexible, hydropower possesses unique operating constraints and complexities that make it unclear that integration with wind power is advantageous or even practical in some cases. As a consequence, there are many misconceptions about the feasibility of wind/hydro integration across a range of issues: its impacts on system operation and balancing including costs to address these impacts; its economic feasibility; its impact on the transmission system and system reliability; and its effect on spill and hydropower constraints (in particular, non-power constraints due to environmental considerations).

The purpose of the present chapter is to describe power system operation and balancing in systems with wind power and hydropower, drawing upon the Task 24 case studies and other relevant literature. At the end of Section 1.2, a set of questions were presented that motivated the formation Task 24. These questions and outcomes are addressed in the subsections to follow, which include an overview of important results from recent wind integration studies, a review of the information summarized in the "State-of-the-Art" report produced by IEA Wind Task 25 on the "Design and operation of power systems with large amounts of wind power" (Holttinen et al. 2008), and a summary of the Task 24 case studies and their findings related to the Task 24 questions and expected outcomes (refer to Section 1.3.5).

4.2 Wind Power Impacts in Systems with Hydropower

4.2.1 Results from Recent Wind Integration Studies

Wind integration efforts have been conducted in an assortment of electrical system balancing areas across the globe, in systems ranging from small to large, using a variety of methodologies, at different wind penetration levels in a variety of power system structures (e.g., market systems, generation fleets). Over the past several years, common methodologies have arisen as a result of industry experience with wind integration studies. Depending on the information sought in a study, techniques ranging from simpler, purely statistical techniques, to more complex cost production simulations that model transmission system constraints and the decisions made in operation of the power system. An overview of these methodologies is provided in Volume 2 of this report, Section 1.1. Almost regardless of the method, the impacts of wind integration are deduced by comparing operation of the system to meet load demand compared to meeting the load demand less the wind power (*load net wind* or *net load*). Furthermore, it is crucial in analyzing wind integration impacts and costs that the system (balancing area) be considered in whole, or some transmission constrained subset of the balancing area. In performing a study, whether simple, detailed, or evolutionary (as discussed in Volume 2, Chapter 1), it is important to consider the effect of wind integration on the entire balancing area, and not to consider a wind power plant in isolation (for example, to try to create a flat output from a single wind power plant by "firming" it with hydro or other type of power). With this system-wide perspective, the wind integration cost is defined as the difference in cost to operate the system with increased variability and uncertainty due to wind power versus cost to operate the system in some fashion without those influences.

There are now a large number of studies related to wind integration and interconnection in the literature. A listing of a majority of these studies, in excess of 670, is in the bibliography provided in Appendix A. The reports are organized by country of origin, and author/title, with a link to the report if available on-line. Of these many reports, a small subset are comprehensive reports that describe complete wind integration studies and present wind integration costs. Wind integration costs are generally reported as ancillary services costs attributed to the addition of wind power to current system operations, typically reported as an incremental integration cost at various levels of wind penetration.

Table 15 gives a summary of integration costs from several U.S. studies (Wiser 2009). These costs are not unlike those found in studies outside the United Sates, where the total integration costs are on the order of 1/10th the cost of the wind energy itself. As presented here, the integration costs relates to the bottom section of the red bar shown in Figure 7. Note the wind capacity penetration is listed as a key parameter in differentiating the studies shown in the table. There are a number of potential methods to define the wind penetration (see Volume 2, Section 1.2); in this table, it is defined by dividing the nameplate wind power capacity by the peak load of the system.

Table 15. Wind integration costs in U.S. dollars per MWh of wind energy produced from several recent studies in the United State (Source: Wiser 2009)

Date	Study	Wind Capacity Penetration	Integration Cost ($/MWh) Regulation	Load Following	Unit Commit.	Gas Supply	TOTAL
2003	Xcel-UWIG	3.5%	0	0.41	1.44	na	1.85
2003	We Energies	29%	1.02	0.15	1.75	na	2.92
2004	Xcel-MNDOC	15%	0.23	na	4.37	na	4.60
2005	PacifiCorp-2004	11%	0	1.48	3.16	na	4.64
2006	Calif. (multi-year)*	4%	0.45	trace	trace	na	0.45
2006	Xcel-PSCo	15%	0.20	na	3.32	1.45	4.97
2006	MN-MISO**	31%	na	na	na	na	4.41
2007	Puget Sound Energy	12%	na	na	na	na	6.94
2007	Arizona Pub. Service	15%	0.37	2.65	1.06	na	4.08
2007	Avista Utilities	30%	1.43	4.40	3.00	na	8.84
2007	Idaho Power	20%	na	na	na	na	7.92
2007	PacifiCorp-2007	18%	na	1.10	4.00	na	5.10
2008	Xcel-PSCo***	20%	na	na	na	na	8.56

* Regulation costs represent 3-year average.
** Highest over 3-year evaluation period.
*** This integration cost reflects a $10/MMBtu natural gas price scenario. This cost is much higher than the integration cost calculated for Xcel-PSCo in 2006, in large measure due to the higher natural gas price: had the gas price from the 2006 study been used in the 2008 study, the integration cost would drop to $5.13/MWh.

4.2.2 Review of Results from IEA Wind Task 25

As described in Chapter 1, integration of wind power into power systems is an active area of research and, as pointed out previously, there have been numerous publications related to the topic including some produced by the IEA (e.g., IEA 2005, IEA 2008a). IEA Wind established R&D Task 25 in 2005 on the "Design and Operation of Power Systems with Large Amounts of Wind Power." This task deals specifically with issues related to wind integration impacts, costs, and analysis techniques. Tasks 24 and 25 bear many similarities centered around wind integration, but Task 24 focuses on systems with hydropower. Because it is of bearing here, and because there is no desire to repeat the good work accomplished in Task 25, a summary of some of the key findings from Task 25 as presented in the "State of the Art" report (Holttinen et al. 2008) and relevant to Task 24 will be presented here. These results are generally applicable to systems with and without hydropower, though they do not include the focused study on hydropower interactions that are part of the Task 24 case studies. Following this section, the findings of the Task 24 case studies that specifically deal with systems with hydropower will be presented.

In Task 25, the integration costs were divided into components originating from grid expansion costs and operational balancing costs. Grid expansion costs are attributed to costs arising from grid reinforcements or expansions required to deal with handling large power flows and maintaining stable voltages, which are particularly of importance in weak grids where the generation is located far from load centers (common for wind power plants). Because this issue is independent of whether the system has hydropower or not, it will not be addressed here. The operational balancing costs, however, are dependent upon whether or not the system has hydropower, and how the hydropower is modeled and deployed in simulating these systems. The results of Task 25 were based upon studies conducted in 22 wind integration studies contributed by members of the Task, as summarized in Table 16.

Table 16. Power system size and wind power penetration studied in national cases (Source: Holttinen et al. 2009)

	Load			Inter-connect capacity	Wind Power					
					2008	Highest Studied		Highest Penetration Level		
Region / Case Study	Peak MW	Min MW	TWh/a	MW	MW	MW	TWh /a	% of peak load	% of gross demand	% of (min load + interconn)
West Denmark 2008	3,700	1,300	21	2,830*	2,380	2,380	5	64 %	24 %	58 %
Denmark 2025 a)	7,200	2,600	38	5,190*	3,150	6,500	20.2	90 %	53 %	83 %
Denmark 2025 b)	7,200	2,600	38	6,790*	3,180	6,500	20.2	90 %	53 %	69 %
Nordic /VTT	67,000	24,000	385	3,000*	4,772	18,000	46	27 %	12 %	67 %
Nordic+Germany/ Greennet	155 500	65,600	977	6,600*	28,675	57,500	115	37 %	12 %	80 %
Finland/VTT	14,000	5,900	90	2,280*	143	7,300	16	52 %	18 %	89 %
Germany 2015/Dena	77,955	41,000	552.3	10,000*	23,903	36,000	77.2	46 %	14 %	71 %
Ireland/ESBNG	6,500	2,500	38.5	0	1,002	3,500	10.5	54 %	27 %	140 %
Ireland / SEI	6,900	2,455	39.7	900*	1,002	1,950	5.1	28 %	13 %	58 %
Ireland 2020/All island	9,600	3,500	54	1,000	1,002	6,000	19	63 %	35 %	178 %
Netherlands	25,200	9,000	127	7,350	2,225	10,000	35	40 %	28 %	61 %
Mid Norway/SINTEF	3,780		21			1,062	3.2	28 %	15 %	
Portugal	8,800	4,560	49.2	1,000	2,862	5,100	12.8	58 %	26 %	92 %
Spain 2011	53,400	21,500	246.2	2,400	16,754	17,500	46	33 %	19 %	73 %
Sweden	26,000	13,000	140	9,730*	1,021	8,000	20	31 %	14 %	35 %
UK	76,000	24,000	427	2,000*	3,241	38,000	115	50 %	27 %	146 %
Minnesota, U.S., 2004	9,933	3,400	48.1	1,500*	1,752	1,500	5.8	15 %	12 %	31 %
Minnesota, U.S., 2006	20,000	8,800	85		1,752	6,000	21	30 %	25 %	68 %
New York, U.S.	33,000	12,000	170	7,000*	882	3,300	9.9	10 %	6 %	17 %
Colorado, U.S.	7,000		36.3		1,068	1,400	3.6	20 %	10 %	
California, U.S.	64,300	25,000	304		2,517	12,500	34	19 %	11 %	
Texas, U.S.	65,200	16,000	317		7,116	15,000	54	23 %	17 %	

** The use of interconnection capacity to countries outside the modeled area is not taken into account in these studies. In the Nordic 2004 study, the interconnection capacity between the Nordic countries is taken into account. In Nordic+Germany/Greennet study the 5 modeled countries are divided into 12 regions interconnected by transmission lines, thereby including the influence of interconnection capacity between countries within the modeled area.*

A summary of the Task 25 results for increase in balancing requirements, presented as a increase in reserve requirement as a percent of the increase in wind capacity is shown in Figure 39. The results here indicate that as the wind penetration increases, the percent reserve requirement also increases, and that the increase is below 10% in all cases. The costs associated with the increases in reserve requirements for several studies are shown in Figure 40. These costs are consistent with those presented in Figure 39, and also indicate that as the wind power penetration increases, the costs to handle the ancillary services (reserves) also increase per megawatt-hour of wind energy produced. In interpreting these results, and in particular the spread in the results, it is important to understand that there are differences in the study methods employed, the wind resources, the system operational characteristics, and the load.

Regardless of the differences between the various studies presented, some general conclusions could be drawn:

- Spreading the wind power over a large geographical region tended to smooth out the variations and reduce the integration costs.
- If the interconnections with neighboring systems were permitted to assist in balancing the system, then wind integration costs were reduced.
- Allowing for changes in schedule to be made closer to the delivery hour tended to decrease integration costs.

Of importance in all these studies were the size of the system and the inherent flexibility of the generation fleet and operational setup to deal with system uncertainties and variations in net load. The more flexibility a system possesses, the more aptly it can deal with the variability and uncertainty of wind energy.

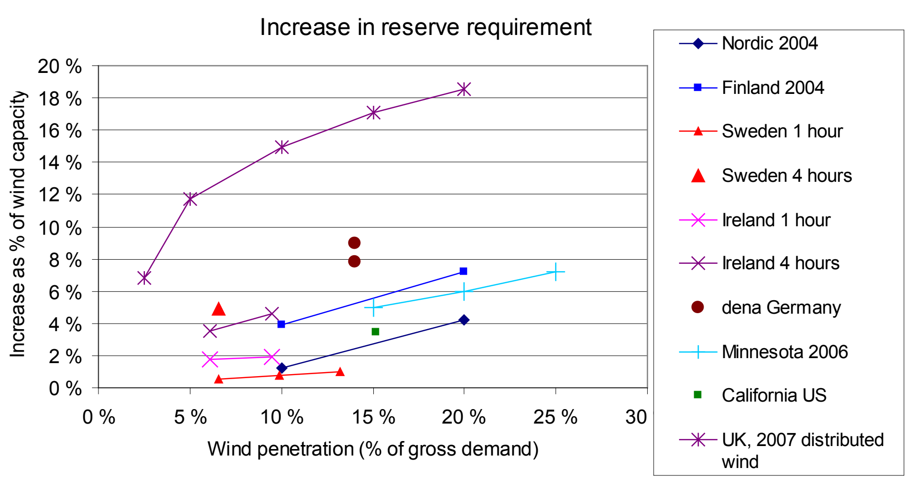

Figure 39. Results for the increase in reserve requirement due to wind power (Source: Holttinen et al. 2009)

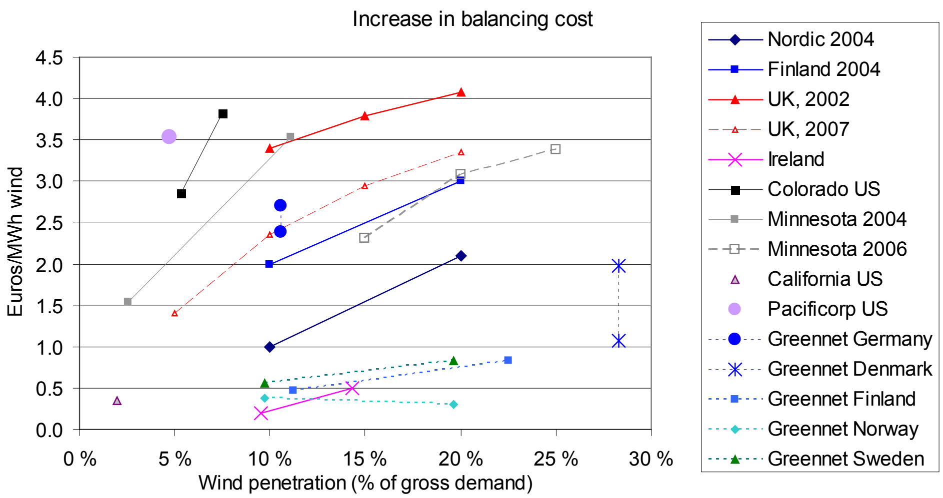

Figure 40. Results from estimates for the increase in balancing and operating costs due to wind power; the currency conversion used here is 1 € = 0.7 £ and 1 € = 1.3 $ U.S. (Source: Holttinen et al. 2009)

Another important consideration that was investigated in Task 25 was the capacity value/credit of wind power. Many system expansion plans are developed around the need for peak capacity, and therefore the capacity that a resource can be relied upon during the peak hours of the year (e.g., the ELCC) is vital. A summary of the capacity credit attributed to wind power for several of the Task 25 case studies is presented in Figure 41. The capacity credit tends to be higher at low penetrations of wind power, and range from a high near the capacity factor of the wind power plant to 5% at high levels of wind penetration (> 30% of gross demand).

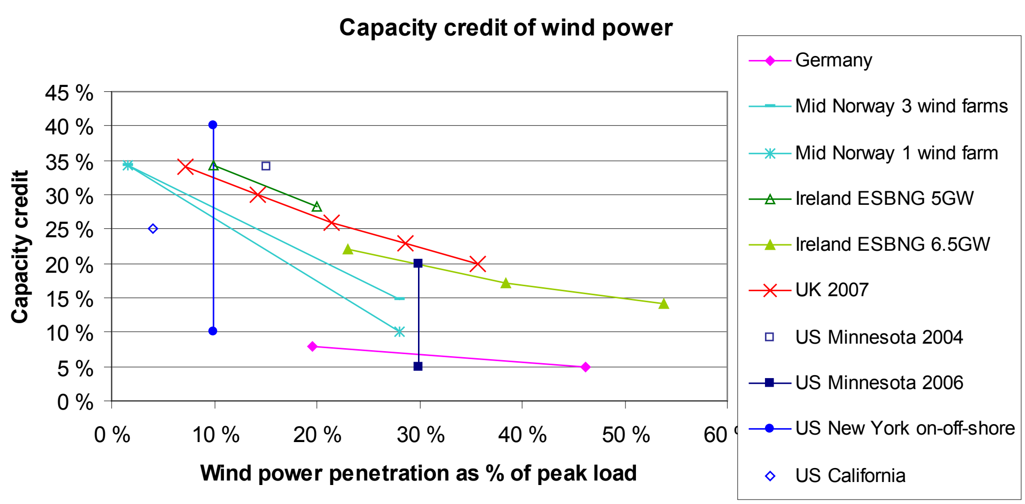

Figure 41. Capacity credit of wind energy as computed in several of the Task 25 case studies (Source: Holttinen et al. 2009)

4.2.3 *Wind Integration in Systems with Hydropower: Summary of Results from Participant Case Studies*

Volume 2 of the Task 24 Final Report deals primarily with the wind/hydro integration study methodologies and presents the case studies performed by each of the participating organizations. Each of the case studies addressed a subset of the questions posed in forming the

Task. In this section, a short description of each case study is provided followed by the key results pertaining to the task work plan. Study presentations are organized by the country of origin. More detail on these studies can be found in Volume 2.

4.2.3.1 Australian Case Studies

Hydro Tasmania is Australia's leading renewable energy business, providing renewable energy to the national grid and trade energy and environmental products in the National Electricity Market. The studies in this section are based on Hydro Tasmania's power system. Because of the potential for significant integration of wind power into the hydro-dominant Tasmanian power system, or provision of ancillary services to the greater Australian system (load net wind), Hydro Tasmania carried out the following three studies to address various aspects of wind integration.

Case Study 1: Large-scale wind integration to the Tasmanian system

Case Study 2: The costs of wind-firming service provided by a hydro plant

Case Study 3: Inertia support in a hydro, wind, and high-voltage direct current (HVDC) hybrid power system

For the purposes of these studies, Hydro Tasmania's system was modeled with 1,850 MW of peak load, a 900-MW minimum load, and 630-MW/480-MW export/import capability via an HVDC interconnect with the Australian mainland. Conventional generation comprises mostly hydropower generation with a mixture of storage and run-of-the-river schemes (2,267 MW). The installed capacity of thermal generation is 400 MW, and the capacity of wind generation is 140 MW. The HVDC interconnector links the Tasmanian power system to the four-state network on mainland Australia. The Tasmanian power system is small in comparison to its largest generator (210 MW) or load (200 MW), and the frequency standards have been recently tightened for a single contingency to 48.0–52.0 Hertz. System capacity is managed in the short- and medium-term through the Projected Assessment of System Adequacy. This covers a 2-year window of power generation and consumption. Daily dispatch is undertaken as a 24-hour pre-dispatch followed by a 5-minute look-ahead during actual dispatch. The Australian National Electricity Market is a spot market based on 5-minute dispatch intervals (and bids). The market price is set by the marginal generation bid. The market objective is to supply energy at the least cost; practically, this is a constrained least cost due to the limited physical capability of the power system. There is a co-optimization between the spot energy market and the FCAS market. The FCAS market and the mechanism by which constraints apply to the energy market is the focus of these studies.

Case Study 1: Large-Scale Wind Integration to the Tasmanian System

Case Study 1 had the objective of identifying limits for the penetration of wind generation in Tasmania based on power system performance. The initial studies concluded that in order to ensure the security of the power system with a minimum system load of about 900 MW, together with 300 MW of import to Tasmania through the (then) proposed Basslink HVDC interconnector, wind generation would have the following implications:

- Between 130 MW and 150 MW of wind generation would require very little change in system operation.

- Operation with between 150 MW and 300 MW of wind generation would require increased FCAS (balancing[15]) operation from conventional synchronous plant or advanced wind-plant control systems.

The more recent 2009 Transend Study shows that up to 1,300 MW of wind generation could be incorporated into the Tasmanian system with Basslink in service if mitigation measures are put in place to support system interia. This figure reduces to approximately 620 MW with Basslink out of service. In both cases, higher wind penetrations would occasionally require wind generation curtailment. Current minimum system inertia is between 3,500 MW and 4,000 MW. Under the new frequency operating standards for Tasmania, system inertia will need to be maintained above the current minimum. Because there are many hydro generators in Tasmania that can operate in synchronous condenser mode, one possible mechanism is to bring generators online in this mode when inertia falls below minimum levels. Synchronous condensers are traditionally used for voltage control support; however, they also provide inertia and fault contribution to the system as added benefits. Where new supplementary voltage control equipment or dynamic reactive power sources are required, synchronous condensers should also be considered in place of power electronic devices (e.g., switched virtual circuit, static synchronous compensators), which do not provide inertia and fault contribution.

Case Study 2: The Costs of Wind-Firming Service Provided by a Hydro Plant
Case Study 2 evaluated the impact on the storage system of installed wind generation, assuming coordinated operation. Two systems are investigated, including operation of an islanded system and an interconnected system within the Australian mainland. For an isolated system, the wind displaces hydro generation—during wet, windy periods this results in a considerable increase in spill. The interconnected system provides much better opportunities for additional wind generation to either be stored or exported to the mainland system without incurring spill. For the purpose of this study, *wind firming* implies the service of supporting wind power production that is assumed to have a "firm" 40% capacity factor (40% is a typical, if not low, capacity factor for a Tasmanian wind resource).[16] If the wind production falls short of 40% capacity during any given hour, the energy shortfall between hourly wind generation and firm capacity is valued at the spot market price. Wind energy in excess of the firm capacity is sold into the market. Thus, *wind firming* refers to the service of guaranteeing a firm capacity from the wind power production on a yearly basis, via use of the hydro storage system (either storing water when wind is in excess of its firm capacity or spilling if necessary, and using water for generation when wind production falls short), with energy transactions valued at the spot market price. Two systems were considered: the first covering an isolated operation of a Tasmanian system and the second covering interconnected operation. The study focused on the efficiency of water storage and spill control.

Interconnected operation reduces monthly spill of generated energy from 30–50 GWh to less than 2 GWh. The annual spill of hydro energy varies between 50 GWh per year to 200 GWh per annul under isolated operation. This amount is reduced to approximately 10 GWh per year with

[15] In the Australian National Electricity Market, the balancing function is provided by FCAS products offered into a 5-minute market and co-optimised with energy.
[16] It is worth noting that most utilities do not sell wind energy as "firm" capacity. A few, however, do this as can be of value to the purchaser if the capacity of the wind is guaranteed (versus simply taking the energy that the wind produces, whether less than or more than the annual capacity factor during any given hour).

interconnected operation. Even with 500 MW of wind generation, interconnection reduces the spill to about 100 GWh after 10 years. The same spill would have occurred with less than 100 MW of wind generation in a case of isolated Tasmanian system operation.

Isolated Tasmanian System
In the case of islanded operation of a Tasmanian power system, the system is unable to effectively absorb all output from large-scale wind generation due to coincident of high winds and high inflows. There is an increasing negative impact on storages as wind generation capacity is increased. The system energy yields (hydro and wind) in the first quarter of the year critically determine how large this effect is. Also, the coincidence of high wind and hydro inflows in the period between September and November led to a small increase in spill. Coincidence of low wind and hydro inflows in the period between February and June resulted in a greater requirement on the hydro system to meet load when storages are low. Under such conditions, there may be minimal reduction of using stored water.

Tasmanian System Interconnected with Mainland
The addition of the high capacity interconnection (HVDC, 600-MW export and 480-MW import) with Australian mainland is a major improvement, allowing the ability to significantly increase penetration of wind generation in Tasmania without a negative effect on the energy in storage. A small increase in system spill is noted. The expected marginal cost of "firming up" wind generation can be as high as $14AUD/MWh at 500-MW installed capacity. Firming of wind increases the average production costs of wind power by $3 AUD /MWh in a case of 100-MW wind development, and $8AUD /MWh in a case of 500-MW wind power development.

Case Study 3: Inertia Support in a Hydro, Wind, and HVDC Hybrid Power System
Case Study 3 focused on operating issues typical for a small system. The main issue is the effects of large-scale wind generation displacing hydro generators and resulting in very low system inertia and an associated high rate of change of the frequency during system disturbances. The study identified that the limiting factors in developing wind generation in Tasmania are due to low system inertia and very fast frequency changes affecting the operation of back protection schemes (i.e., under-frequency load shedding). The report also identified that commitment of additional hydro generators operating in either synchronous condenser mode or tail water depression mode can largely improve the integration of the wind generation in Tasmania. In particular, the use of tail water depression mode allows fast machine start up from motoring operation and provides three valuable services including voltage/reactive power control, additional inertia, and additional FCAS. However, at present, inertia is not a recognized market service and the work on recognition of this service is not accepted as an off-market service, as is the case for reactive power support.

Large penetration of wind generation in the isolated hydro system would result in commitment of fewer hydro generators under strong wind conditions. Also, generators in service would operate at lower than efficient output. This situation is made more difficult with the HVDC interconnector. Recent experience in Tasmania shows that some generators operate at output as low as 10% to increase system reserves (i.e., FCAS) and to make the system heavier (i.e., add inertia).

The cost of low output operation is high due to low efficiency. Increased cavitation damage and higher maintenance requirements have also been reported. The cost of supplying additional inertia in the hydro-based system with machines capable of operation as synchronous condensers or in tail water depression mode is low in comparison with the potential benefits. The cost of motoring relates to a load of about 2% of machine rating. These benefits include the following:

- Allows maximization of inter-connector flows
- Allows greater fraction of inertia less generation (variable speed doubly fed induction generator wind generation) in Tasmania
- Improves efficiency of using water comparing to low load operation
- Reduces maintenance requirements on hydro units

4.2.3.2 Canadian Case Studies

Natural Resources Canada, Hydro Québec, and Manitoba Hydro all participated in Task 24 on behalf of Canada. For reasons associated with utility approval to release detailed study information, neither Manitoba Hydro nor Hydro Québec were able to contribute case study reports to the Task 24 final report, though they were routine contributors at the R&D meetings. Natural Resources Canada did conduct a study and contributed it to the task, as described below. Its study focused on the economic impact and feasibility of incorporating wind power to cover load growth using its RETScreen[17] project analysis tool.

The RETScreen analysis sought to evaluate the economic effects of integrating wind generation into Okanogan PUD in Washington State, U.S., a small, hydro-dominated utility that is often required to purchase power from the market to supplement the scheduled resources. Okanogan PUD purchases all of its power, approximately 60% of which is supplied by the Bonneville Power Administration and 30% by the Wells Hydroelectric Project. The purpose of the study was to determine if the additional energy procured by wind at the proposed rate would be economically favorable to purchasing power from the market when supplementary amounts are needed. Particular attention was paid to wind resource availability during times of drought, when hydro resources are strained and market prices tend to be higher. This study differs from most of the other case studies that have been contributed to Task 24; it is an economic evaluation of incorporating wind energy into a system versus other alternatives (an estimate of the value of wind energy), and not a grid integration study that seeks to determine the impacts and costs of wind power's variability and uncertainty.

The Okanogan PUD system has a dual peak in the winter and summer of approximately 145 MW. Its average load is about 90 MW (based on an assumed 60% system load factor). Its generation resources are almost entirely hydroelectric (86%) with several flow restrictions through dams located on the Mid-Columbia River. Okanogan PUD was interested in acquiring 25% of the power output from the 64-MW Nine Canyon Wind Farm project. On a capacity basis, this amounts to about 16 MW, or 11.4% of the peak system load levels of 140 MW. On an energy basis, this would amount to approximately 7% of the annual energy requirement for the utility, given an estimated capacity factor of 31.4%.

[17] See http://www.retscreen.net/ang/home.php; RETScreen stands for Renewable-energy and Energy efficient Technologies Screening tool, and was develop for Natural Resources Canada.

Wind variability is smoothed/handled by the Load Control Area operator for Douglas County PUD at the Wells Dam on the Columbia River. This also allows Okanogan PUD's share of the wind power to be delivered at a later time. The study found that the amount of wind being integrated from the Nine Canyon Project would lead to minimal need for additional ancillary services, as fluctuations in wind power production would hardly alter the utility's existing load swings.

The conclusions of this study offered a comparison of the parameters that were predicted by the RETScreen analysis and those that were encountered in reality. The actual wind power delivered over the 3-year period of 2003–2005 was about 90% of that predicted to be normal by the RETScreen procedure. The net cost of delivered wind energy during this period was $44.1 CAD/MWh, which exceeded the cost of $43.9 CAD/MWh that would have been accrued if the energy had been purchased from the market. This negative value was made up for when the utility sold Renewable Energy Credits during 2005 for $3 CAD/MWh, resulting in a positive net value of $37,000 CAD for the wind power over the 3-year period. The report also concluded that the wind purchase would not have been economically favorable without the Renewable Energy Production Incentives.

The study highlighted results showing the ease of integrating wind into a hydro-centered Load Control Area, as balancing costs were kept at $0.9 CAD/MWh instead of the $4.5 CAD/MWh that would have been required for purchasing balancing services from Bonneville Power Administration. It suggested that there would be minimal requirements for additional ancillary services due to wind because the Load Control Area operator easily smoothed fluctuations by using hydro flexibility. For the years studied, a positive correlation was found to exist between periods of drought and low wind for the region. This corresponded to an increase in both the cost and value of available wind power. However, market prices were also found to be higher during these same periods, helping to maintain the economic position of purchasing wind power.

4.2.3.3 Finnish Case Studies

The Technical Research Centre of Finland (VTT) conducted two case studies on behalf of Finland:

- A case study focusing on the handling of wind power prediction errors for a single hydrothermal power producer in Finland
- A summary of the impacts of a wind- and hydro-dominated power system on the electricity markets and the characteristics of Nordic hydropower

For the purpose of these studies, the word *regulation* is used to mean 10–15-minute balancing, and *balancing market* refers to what is officially called the Regulating Power Market in the Nordic countries—the more neutral word *balancing* is also used.

Case Study 1 was performed to see the possibilities of a hydrothermal power producer with limited regulation possibilities to balance wind power in its portfolio. This case study is based on one producer using the Nordic electricity market. The producer has 400 MW of run-of-the-river hydropower with very limited storage possibilities. Wind power generation is forecast 1 day ahead, and balancing can be done at the market (paying imbalance prices of forecast errors; part of the forecast errors can be dealt with intra-day trade) or by the producer internally by adjusting hydropower production.

The case study was based on 1 year of data. A time series of forecast errors for 9 MW of wind in 2004 was increased to 200 MW and 400 MW of wind power (representing 50% and 100% of the hydro producer's installed capacity, respectively). The first step in the study was pricing imbalances at current Nordic market rules (2004 price data). The second step was using 2004 prices for intra-day market pricing (closing 1 hour before delivery) to calculate how intra-day trading would reduce imbalance costs. The third step was looking at the possibilities of hydropower to handle the imbalances, which was done by looking at the time series of produced hydropower in 2004 and calculating how much of the forecast errors of wind could be corrected by shifting hydropower production some hours. Limits for minimum and maximum hydropower production were kept the same, and the total energy for each day was kept at ±10 % of the original time series.

Wind power penetration in Finland was less than 1% of gross demand (energy) and less than 3% of peak load (capacity). Two wind power scenarios, 200 MW and 400 MW, were studied, which were 50% and 100% of the producer's installed hydropower capacity. The study assumed that wind power in Finland (200–400 MW) would not affect the market and balancing market prices. A limitation of the study is that a simulation was not performed to estimate how much hydropower energy could be shifted from 1 day forward.

The study concluded that the imbalance costs from day-ahead forecast errors for aggregated wind power in Finland is roughly € 0.62 /MWh, when calculated per megawatt-hour total produced. The cost of regulation, when there is an extra cost, is on average € 3–4 /MWh. But, more than half of the time, the wind power imbalance is opposite to the total system imbalance. For those hours, the only cost effect is the fixed volume cost of € 0.7/MWh for the imbalances. These results apply for the Finnish power system in which wind power is not affecting the price level or direction of regulation used in the power system. Also, the balance settlement rules affect the results—the use of a one-price model instead of a two-price model would drop the balancing costs to near zero.

Compared with leaving all day-ahead forecast errors to balance settlement, Elbas trading is only cost effective when trading close to spot price levels (Elbas is an intra-day market to cover anticipated imbalances between the load and generation, see Figure 5). Actively trading to reduce the forecast errors of wind means making trades almost all the time. Leaving the forecast errors to imbalance settlement means that more than half of the time there is no penalty. Approximately 60% of the time, there is only a € 0.7/MWh volume fee for the imbalances; usually the Elbas trade is not cost effective. Additionally, 400 MW of hydropower could provide internal balancing to correct 83% of prediction errors for 200 MW of wind power. For 400 MW of wind power, 63% of the imbalances could be balanced internally. Using hydropower to balance wind power imbalances is profitable for both parties. Depending on the price set for the internal balancing and the wind power capacity, the balancing costs for the wind power producer would be reduced by roughly 20–85%.

This study showed that even with the limited flexibility of hydropower (run-of-the-river with small reservoirs), a large part of wind power forecast errors can be provided for by shifting hydropower back and forth inside 1 day. This is because the wind power forecast errors average zero, so both up- and down-regulation are used and the side of balancing varies from up to down and back frequently. The study also showed that when correcting the forecast errors of wind power at a large balancing market in which hydropower produces most of the balancing (like in Nordic countries), there is not a great benefit of combining/integrating wind power and hydropower at a single producer. It is more cost effective to bid all flexibility of hydropower to the balancing market and use it from there to correct the system imbalances than to use it for dedicated balancing of wind power.

The second Finnish case study analyzed the impacts of a wind- and hydro-dominated power system on the electricity markets and the characteristics of Nordic hydropower. In reference to the intended outcomes of the report relative to the objectives of Task 24, the market model WILMAR was used to model the behavior of the Nordic system with different wind power penetrations. The study analyzed the adequacy of hydropower to smooth the variability of wind power, the effects of combined very large penetration of wind power and hydropower on spot prices, and the use of transmission lines and conventional power plants due to increased wind power production. The most important limitations arising from chains of stations and reservoirs were taken into account. This river system model was used to check the accuracy of dispatch from a more coarse market model, which aggregated the hydropower plants into larger groups. The database for the hydropower plants and reservoirs enabled a more accurate and detailed aggregation of hydropower in the market model.

The Nordic system has an estimated peak load of 74,000 MW (2010 estimate) and gets 60% of electricity from hydropower, of which most have large reservoirs. Conventional generation capacity was estimated at 93,000 MW in 2010 with 2,360 MW of transmission interconnections. The study analyzed wind power energy penetrations of 10%, 20%, and 30%, with the intention of determining whether or not there is enough regulation available from the hydropower to deal with wind power variation and forecast errors. The model had stochastic wind power presentation. Since a significant amount of wind power was added and only little conventional capacity was retired, system adequacy was not an issue. The study also examined the effect of a large amount of low marginal price production on market prices, including assessment of hydropower plants participating in the regulation market.

The study concluded that a large penetration of wind power in a hydro-dominated power system will lower the spot price of electricity dramatically, which creates a challenge to get new investments in the system. It is unclear whether this kind of system could arise based on the markets even if it would be the most cost-effective way to serve load from a system perspective. It appears that the regulation capacity of hydropower in the Nordic countries is large enough to support at least 30% wind energy penetration.

Because the Nordic system has thousands of hydropower plants and more than a thousand reservoirs, it has to be aggregated for a market model in order to keep the model solvable. The study aggregated hydropower based on a database of river systems and on analyses of the restrictions that river systems and reservoir sizes place on the use of hydropower. Results show that a large part of hydropower capacity should be capable of flexible operation.

Relative to these conclusions, the expected results of Wind Task 24 for this study are as follows:

- The study identified a practical system configuration of 60% of electricity from hydropower, most of which being reservoir hydropower, and 30% of electricity from wind power. Because old power plants were not retired, there were no problems with system adequacy.
- A large penetration of wind power in a hydro-dominated power system will lower the spot price of electricity dramatically, which creates a challenge to get new investments in the system. It is unclear whether this kind of system could arise based on the markets even if it would be the most cost-effective way to serve load from a system perspective.

4.2.3.4 Norwegian Case Studies

Because the wind resource in Norway is well correlated with the load, and due to the large amount of hydropower generation that is present, the Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF) investigated the ability to integrate wind and hydropower. For the purpose of the Task 24 research, two case studies were contributed:

- The first study looked at wind power in areas with limited power transfer capacity and subject to grid congestion. The question to be addressed here was to see how much wind power could be integrated without deleteriously affecting the hydropower production.
- The second case study considers the impact of wind power on system adequacy. Considering that the region has favorable wind resources, the study was conducted to determine whether or not adding wind power to the hydro-based system will be sufficient or if additional measures must be taken to secure system adequacy.

The first SINTEF case study considered wind integration into an area of the Nordic system with limited power transfer capacity. When planning wind power in areas with limited power transfer capacity, conservative assumptions may lead to unnecessarily strict limitations on the possible wind installation. By introducing AGC and coordinated power system operation, a large increase in installed wind power is viable.

The purpose of this study was to assess grid integration of large wind farms subject to grid congestions. Emphasis was put on how different control strategies for handling congestion situations affect the operation and economics of the studied regional power system. When assessing the impact of wind power on the power system operation, it is necessary to take into account the variable and dispersed nature of wind power. This study and previous studies have shown that in the Nordic region, the periods with highest wind generation typically appear in the winter season when the consumption also is high, which has a positive impact on utilization of the existing transmission capacity. Moreover, this study showed that the power smoothing effect of geographically dispersed wind farms gives a significant reduction of discarded wind energy in constrained networks, compared to a single up-scaled wind farm site.

The specific case study presented consists of a regional power system with assumed 420-MW power transfer capacity. With regard to integrating wind energy, the most conservative approach allows for only 115 MW of wind power in the constrained network with 420 MW of capacity, as this will not require any control actions even in the very unlikely case of maximum wind and hydro generation (115 MW + 380 MW) at the same hour as the historically lowest consumption (75 MW). However, the viable amount of wind power that can be installed is expected to be much higher, not only because of the smoothing effect of geographically dispersed wind farms, but also because the periods with highest wind generation typically occur in winter, when the consumption also is at its highest. Since the hydro inflow occurs mostly during summer, this wind characteristic is beneficial for the system operation.

An hourly simulation model of the regional power system was implemented in MATLAB using a 30-year time series of wind output, electricity consumption, hydro flow and generation, and electricity market prices. The Multi-Area Power Market Simulator (EMPS) model, a commercial model developed at SINTEF Energy Research in Norway for hydro scheduling and market price forecasting, was employed to generate several of these time series. EMPS is a complex, stochastic optimization model that simulates the optimal operation of hydropower resources in a region with a stochastic representation of inflow to the hydropower stations and a number of physical constraints taken into account.

The results of the study show that for the specific system studied, up to 600 MW of wind power is possible—without noticeable reduction in income from energy sales compared to an ideal non-congested case—by applying coordinated operation of the wind power and hydropower plants. These results are achieved for a hydropower system with a relatively small reservoir and a high share of non-storable water inflow (37% of the total storable plus non-storable inflow). Even if the local hydropower plant follows the generation schedule unaffected by wind power, the reduction in income due to discarded wind energy is as low as 1% to 5%, depending on the annual wind speed and water inflow. Power system coordination allows for surprisingly large amounts of wind power. It is essential to account for power system flexibility and the variable and dispersed nature of wind power. The methodology presented facilitates this and represents a rational approach for power system integration of wind farms in areas with limited transfer capacity.

The second SINTEF case study analyzed a regional, hydro-based power system with weak interconnections. This case study considered the impact of wind power on system adequacy. The impact was assessed using data from a real-life, regional, hydro-based power system, although data was simplified and fitted for the purpose of the work. The region has a predicted need for new generation and/or reinforcement of interconnections to meet future demand. Considering that the region has favorable wind resources, the study was conducted to determine whether or not adding wind power to the hydro-based system will be sufficient or if additional measures must be taken to secure system adequacy.

System adequacy relates to the ability of the system to meet the load demand. In this study, this was addressed considering (1) the system's ability to supply the annual load and (2) the system's ability to meet the peak demand. The system's ability to supply the annual load was assessed using 30 years of recorded data of hydro inflow and wind speed. The system operation was simulated to quantify annual energy balance within the region, including hydro, wind, and import/export through interconnections with neighboring regions.

The system ability to meet the peak demand was assessed by calculating the loss of load probability for the system, using standard statistical techniques (see Section 5.3.3 of Volume 2 for more details). The calculation takes account for the installed generation and transmission capacity, the probability of outages, and the probability of wind power generation at the hour of peak demand.

Three cases have been considered: the installed wind power is 62 MW (Case B) and 1,062 MW (Case A and Case C), which correspond to 186 GWh and 3,186 GWh of annual generation. With a 3,780-MW peak load, the wind power penetration becomes 1.6% (Case B) and 28.1% (Case A and Case C). The annual load is 21,024 GWh, which gives wind energy penetration levels of 0.9% (Case B) and 15.2% (Case A and Case C).

The study concluded that wind power will have a positive effect on system adequacy in a regional hydro-based power system. Wind power contributes to reducing the loss of load probability and improving the energy balance. Adding 3 TWh of wind or 3 TWh of gas generation are found to contribute equally to the energy balance, both on a weekly and annual basis. Both wind and gas improves the power balance. The capacity value of gas is found to be about 95% of rated, and the capacity value of wind about 30% at low-wind energy penetration and about 14% at higher wind penetration. The smoothing effect due to geographical distribution of wind power has a significant impact on the wind capacity value at high penetration. Indeed, similar results have been reported from various national studies (see Figure 40). The significance of this study is therefore related to the real-life case studied, being a region rather than a national system, and demonstrating the relevance of applying system adequacy studies for generation expansion and transmission planning of regional systems.

4.2.3.5 Swedish Case Studies

Below two Swedish studies will be presented. The first one is a detailed study of one river, where the aim was to simulate how the hydropower along this river can balance wind power, and the second study analyzed how the rivers in the North part of Sweden can balance wind power in the same region. Both studies were conducted by the KTH, the Swedish Institute of Technology.

The first Swedish case study analyzed the possibility of balancing wind power with hydropower plants located along one certain river. The aim of the simulation is to study whether an increased amount of wind power might decrease the efficiency of the hydropower system along an interconnected river system. The study method used was to (1) plan the hydropower system for a week (deterministic approach); (2) simulate changes in wind power production and load during the coming hour; (3) estimate how the power system was operated since it was not according to plan; (4) re-plan the rest of the week; and (5) go back to step 2 until all hours during the week have been simulated. This means that forecast uncertainties concerning both wind power and load were considered, and the hydropower system operation was optimized and re-optimized when new information was available. The model was constrained in that it was assumed that a certain amount of wind power was balanced using hydropower resources in a certain river.

The hydropower system studied consisted of seven hydropower stations with a total capacity of 478 MW, each modeled with installed capacity, varying efficiency (marginal production equivalents) depending on discharge, reservoir capacity for each station and delay time between the different hydropower stations. Wind power penetration was studied for three different scenarios; 30, 60, and 90 MW. The result was then extrapolated in order to draw conclusions for wind power integration in the whole of Sweden. The amount of wind power studied in the certain hydropower system corresponded to a penetration in whole Sweden should equal to 6.5–7.5 TWh/year (i.e., 5 % of total energy production per year). In the extrapolated case, the balancing is assumed to be performed in the whole of Sweden.

The results from the simulations indicate that Swedish wind power installations that generate about 2–2.5 TWh/year do not affect the efficiency of the Swedish hydro system. At wind power levels of about 4–5 TWh/year, it is estimated that the amount of installed wind power should be increased by about 1% to compensate for the decreased efficiency in the hydro system. At wind power levels of about 6.5–7.5 TWh/year, the additional wind power needed to compensate for loss of hydro efficiency is about 1.2%, but this figure has to be verified with more extended simulations.

The aim of the simulation in the second Swedish case study was to study the possibility of balancing wind power in northern Sweden using hydropower in northern Sweden. For each week studied (12 different weeks per year were studied) and wind power level, the method used was to: (1) set up a certain wind power scenario; (2) define a goal for each reservoir level at the end of the studied week including a range of flexibility for this level; and (3) perform a deterministic optimization (linear programming approach) for how to use the available water as efficiently as possible (maximize the production) for the studied week, considering: wind power production, hydrological constraints including juridical restrictions, export capability, local load, and thermal production. Hourly load and wind profiles employed were drawn from the same week and year, whereas the hydro time series was from a typical water year.

The wind power hourly data were simulated wind power series from 19 sites in northern Sweden. Available data were from 1992–2001. The total wind power production was obtained by just summing up the data from the 19 sites since no transmission constraints within the studied area were considered. The simulated series had a total installed capacity of 795 MW and the output was scaled to 1,000; 4,000; 8,000; and 12,000 MW. All hydropower stations larger than 10 MW in the studied area were considered (i.e., 154 hydropower plants with a combined capacity of 13.2 GW), which corresponds to about 80% of the installed capacity of all hydropower in Sweden. These stations were modeled with a variable efficiency at peak production as well as at lower levels (piece-wise linear marginal production curve). Reservoir volumes and constraints, juridical restriction concerning e.g., minimum flow, and delay times between different stations were also considered. Inflows from 2007 (a rather “normal” inflow year) were applied. Twelve different simulations were performed for different inflows, and reservoir start and end limits. However, it has not been possible within this project to develop sufficiently detailed models of season and short-term planning. Also, the modeling of the electricity market is quite simplified. All in all, this results in a model showing which technical possibilities there are to balance wind power variations by hydropower, but more research is required to study how much of this balancing capability will be made available to the electricity market under different regulatory frameworks.

The conclusion of the study was that the existing hydropower in northern Sweden has sufficient installed capacity and is fast enough to balance even large amounts of wind power. The challenge for a large-scale expansion of wind power is to find an outlet for all electricity generation. Improved planning tools can sole this challenge, but it could also be profitable to make investments in, for example, reinforced export capacity. The model predicted spill to occur, but to an overwhelming extent, such a spill can be avoided by using efficient tools for season planning. Only in a few cases—and then, in particular, for a wind power expansion of 12,000 MW—will there be a spill that depends on insufficient balancing capability in the hydropower.

4.2.3.6 United States Case Studies

The case studies contributed by the United States originate from three different river systems and electrical balancing areas, as listed below:

- Missouri River and the Western Area Power Administration
- Upper American River and the Sacramento PUD
- Columbia River and the Grant County PUD

In these studies, each system differs in its basic characteristics related to wind integration: organizations involved and balancing area setup and generation resources, hydro system characteristics, purpose of study, and constraining factors. However, each of these studies did seek to determine the basic impacts of wind integration in terms of the ancillary services required to handle the additional variability and uncertainty that wind power introduces into the balancing area net load. The third study also investigated the impact of wind integration on system flow constraints.

The first U.S. case study analyzed wind integration into the balancing area operated by WAPA and supplied by hydropower facilities located along the Missouri River. This study considered integrating five levels of wind power (80 MW; 100 MW; 250 MW; 500 MW; and 1,000 MW) into the WAPA control area with its peak load of 2,700 MW. Thus, the wind penetration level (defined by wind power capacity divided by peak load) for these cases was 3%, 3.7%, 9.3%, 18.6%, and 37% respectively. The load is currently served by a combination of hydropower plants along the Missouri River system and thermal power plants (coal-fired steam). The hydropower capacity is 2,400 MW from six hydro facilities containing multiple years of water storage.

The most challenging aspect of this study was its organizational complexity. This study was conducted by EnerNex Corporation and Wind on the Wires for NREL, in cooperation with WAPA and USACE. The six hydropower facilities located at the dams within WAPA's Upper Great Plains Region, are run by USACE managed within its North-Western Division as governed by written guidelines in the Missouri River Master Manual (www.nwd-mr.usace.army.mil/mmanual/mast-man.htm). USACE updates this manual each year; provides guidance to the operators at each dam concerning water releases; and incorporates recent and projected hydrological conditions, environmental requirements (e.g., accounting for bird and fish survival), desired lake levels, etc. The dams are all located on the main stem of the Missouri River in the Northern-Midwest United States. This type of organizational complexity is not uncommon for hydropower systems in the United States, and this represents a real challenge for wind and hydropower integration where this is the situation.

The purpose of this study was to perform a statistical analysis to determine the impacts of the wind integration on the system regulation (10-minute variations), load following (hour-to-hour), magnitude of ramping during the morning and evening load ramps, and the effect of wind forecast errors on the aggregate hour-ahead and day-ahead forecast error of load net wind versus load alone. Results of the study led to the following conclusions:

- The amount of "10-minute regulation" capacity that would be required to compensate for the additional fluctuations wind power adds to the system due to variations of the 10-minute net load signal relative to the 2-hour tendency was found to be minimal (≤ 1 MW) for wind penetration levels up to 250 MW (9.3% wind penetration), noticeable (≤ 6.5 MW) at 500 MW (18.6% wind penetration), and substantial (≤ 21.5 MW) at 1,000 MW (37% wind penetration). For the purpose of this study, the "10-minute regulation" is additional generation needed to handle the increase in fluctuations of the net load caused by wind power variations.

- The load following trend—computed via changes in hourly load and compared to changes in hourly load net wind—showed a similar result to the regulation in that the influence of the wind power did not become significant until 500 MW of wind was absorbed into the system.
- Of importance in any electrical system is the ability of the system operator to use available generation resources to effectively and economically meet the morning and evening ramping requirements. The statistical study demonstrated that the load changes during the morning and evening ramping periods were very similar for the load alone and the load net wind, even up to 500 MW of wind power (18.6% penetration). After this level, the wind does impact the ramping requirements, increasing the number of larger ramps that occur and increasing the maximum level of ramping needed during the year.
- In investigating the effect of wind forecast errors, the error in the wind forecast was combined with load forecast errors and then compared to the load forecast errors alone. Due to the existing load forecast errors in the WAPA system, there is little noticeable impact of wind generation on the day-ahead, hour-by-hour forecast until the penetration reaches 500 MW.

In conclusion, the statistical study presented has indicated that in the WAPA system, significant operational impacts from wind energy—those that must be dealt with in planning and operation—will likely arise when the wind penetration approaches 500 MW (about 18% of the peak system load). Below 10% wind penetration, the impacts on 10-minute regulation, load following, morning and evening ramping, and the load net wind forecast error are somewhat modest.

The second U.S. case study focused on hydropower resources along the upper American River and operated by the Sacramento Municipal Utility District. The study focused on the impacts that four proposed penetration levels of wind generation would have on regulation requirements, equivalent capacity values, and integration costs. The primary objective was to assess the stochastic nature of the power produced from additional wind power plants and the impacts they have on the need for additional fast-ramping regulation and load following reserves in the Sacramento Municipal Utility District balancing area. Also investigated was the ability to provide "regulation" from the hypothetical Iowa Hill pumped storage facility.

Hourly simulation cases were completed for at least one full year of data for four proposed wind generation penetration levels. Wind generation data for the all cases was synthesized from the WindLogics Mesoscale Model Version 5 meteorological simulation data for the historical year 2003. Integration cost in this study is defined as the difference between the actual production cost incurred to serve the net of actual load and actual wind generation and production cost from the reference case, where wind is perfectly known and adds no variability to the control area, and where next-day load is the only uncertainty.

The study investigated the affect on the Sacramento Municipal Utility District's control area of the following four levels of wind generation: 102 MW (Case 1), 250 MW (Case 2), 450 MW (Case 3), and 850 MW (Case 4). These correspond to the following wind penetration levels, computed by dividing the wind capacity by peak system load: 2.7%, 6.7%, 12.1%, and 22.8%, respectively. Specifically, the project sought to investigate the effect on the fast regulation requirement and integration costs of wind energy for the different cases. The study found lower penetrations of wind generation have only a small impact on fast regulation requirements, but begin to dominate as the penetration increases. The results show a very substantial reduction in operating cost and integration costs with the hypothetical Iowa Hill pumped-storage facility operating (as much as $5/MWh). Furthermore, the results also show that integration costs decrease with increasing diversity of wind generation assets. Integration cost in this study was defined as the difference between the actual production cost incurred to serve the net of actual load and actual wind generation and the production cost from the reference case, where wind is perfectly known and adds no variability to the control area, and where next-day load is the only uncertainty. A summary of the integration costs are provided in Figure 42, where the four cases correspond to the four penetration levels mentioned above. For each case, five different scenarios of how to handle the enhanced variability and uncertainty of net load due to wind power were considered.

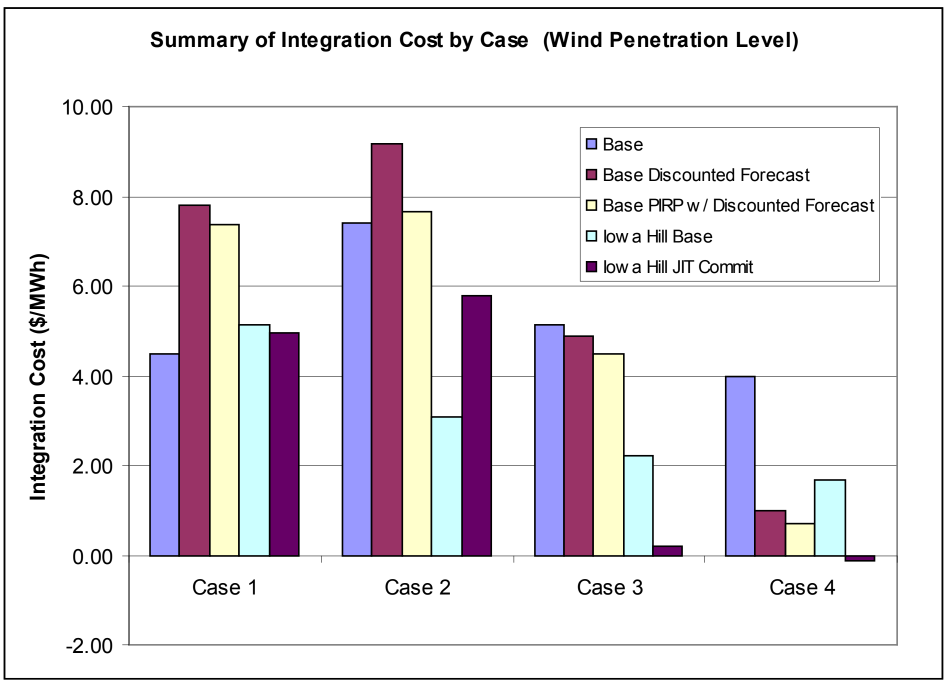

Figure 42. Wind integration costs for four wind integration penetration levels: Case 1 with 102 MW, Case 2 with 250 MW; Case 3 with 450 MW, and Case 4 with 850 MW; these correspond to wind penetration levels as a percent of peak system load of 2.7%, 6.7%, 12.1%, and 22.8%; tor each case, five different strategies for providing system balancing were considered (Source: Zavadil 2008)

The authors determined that the integration cost drops significantly with the wind penetration level. At first, this seems counterintuitive since it would seem likely that more wind would require less efficient commitment to handle the uncertainty and variability in the wind energy delivery. One aspect of lowering the effect of higher wind penetrations is increased geographic diversity. Cases 1 and 2 are concentrated scenarios with all of the turbines in a relatively small area, and are affected by essentially the same meteorology at the same time. In Cases 3 and 4, the wind plants are scattered over a much greater geographic area. This tends to smooth the wind because while one site may have low wind, another may have high wind.

The modeling conducted showed that unit commitment and dispatch become difficult at penetration levels of 850 MW without the Hour Ahead Scheduling Process (HASP), yet work very well at the 450-MW level. Although the cases that include involvement in the Participating Intermittent Resources Program will require fewer reserves to be provided by the Sacramento Municipal Utility District, there are only very small decreases in the integration costs that result from these cases. Changes in the Hour Ahead Scheduling Process market structure could significantly affect integration costs. A more detailed treatment of error analysis will yield more accurate results. Wind forecasting error, load forecasting error, and any relation between the two should be studied.

The third U.S. case study considered two hydropower plants located along the Columbia River and operated by the Grant County PUD No. 2. Grant PUD was interested in studying ways to expand its wind energy generation through effective integration with its two-dam Priest Rapids Project on the Columbia River in central Washington. In addition to its 900 MW of hydropower, Grant PUD purchases a share of the 63.7 MW Nine Canyon Wind Project.

The two primary goals of the study were: (1) to understand the impacts of Grant PUD's current efforts at integrating wind and hydropower, and (2) to study the potential for future expansion of wind integration. In addressing these goals, the Grant PUD sought to understand the impacts of wind integration on its hydro operations, including effects on spill; approximating an economic value for the wind energy; and, most importantly, identifying the frequency and magnitude of surpassing generation limitation or dropping below the minimum flow requirement (for fish survival).

Study results focus on three primary interest areas: (1) wind power effects in the regulation and load following time frames; (2) impacts associated with system planning in the unit commitment time frame; and (3) understanding the impacts on exceeding system constraints related to maximum generation (i.e., keeping sufficient reserves) or minimum flow levels to comply with environmental regulations for fish survival. The penetration levels of wind power penetration considered in the project were 12 MW (1.8%), 63.7 MW (7.8%), and 150 MW (18.6%), computed as a percentage of peak load (including sales of energy).

Study results for the 2006 data year suggest that the overall impact on system statistics for regulation and load following is quite modest, even at a wind energy penetration of 150 MW (~19% wind penetration by capacity). The small statistical impact suggests that, absent other constraints, the physical generation resources are sufficient to handle wind variability at this level. However, due to changes in the distribution of load following hourly changes, there are some potentially significant operational challenges in scheduling the resources without infringing upon system constraints. To assess the impact on system constraints, a pre-schedule (i.e., day-ahead) planning simulation was devised and conducted, using an hourly time resolution. Figure 43 shows the effect of day-ahead wind power forecast errors on the low-load hour minimum capacity “exceedences”[18] (dropping below the minimum capacity, and therefore dipping below the minimum flow permitted). With respect to this limit, the effect is not pronounced as the blue columns shown (representing the number of flow exceedences if incorporating 63.7 MW of wind power and using a day-ahead forecast only) are nearly the same height as the red columns corresponding to the system as run (with 12 MW of wind power), with an increase only in the short-duration violations. Note that no attempt was been made in this analysis to see if the increased exceedences could be averted by real-time or “hour-ahead” transactions. Rather, the intent was to assess the impact on the number of exceedences under a reasonable planning algorithm. These results do show that an increased number of exceedences occur, but that the increase is only modest. It is also possible that many of these instances could be handled during the day of operation, and at some cost. Addressing this latter point would be the next logical step for Grant PUD in continuing this analysis.

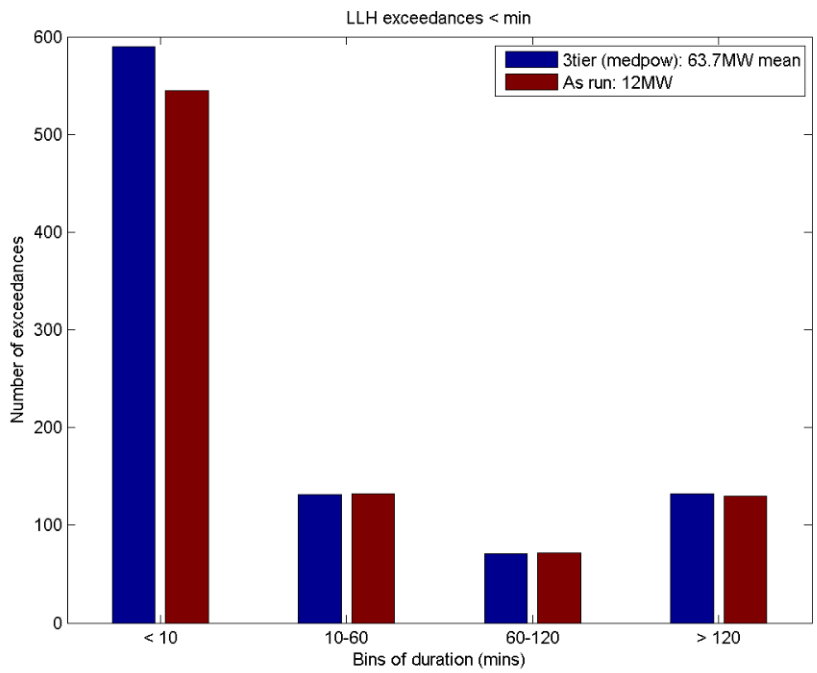

Figure 43. Number of exceedences (dropping below) the minimum allowable capacity due to a flow constraint, for the system as run and with 63.7 MW of wind planned into the system in the day-ahead pre-schedule (Source: Acker 2007)

4.2.4 Practical System Configuration

Figure 44 provides a conceptual view of a practical configuration for combining wind and hydropower in a BA. The key take away from this illustration is that wind and hydropower are system resources that help serve the load via the transmission grid, and that they are each controlled by the TSO. Addressing the incremental impacts of wind integration is done in the context of the entire system, with all of its load and generation resources, and not in isolation

[18] An “exceedence” refers to either one of the following: (1) the hydropower generation level rising above the permitted level for reliability (and thus dipping into the contingency reserves in order to meet the net load) or (2) the generation level being reduced to a level where the flow exiting the second of the two Grant PUD hydro facilities falls below the level required for fish protection downstream of the plant.

from them.[19] It is possible that due to transmission limitations the resources of the entire balancing area will not be available to correct imbalances that arise in transmission constrained area within the BA. In such a case, the configuration proposed remains the same, with the exception that the BA shown becomes the transmission constrained area and responses to imbalances must utilize resources available within the area or those that can be delivered through the transmission constraint.

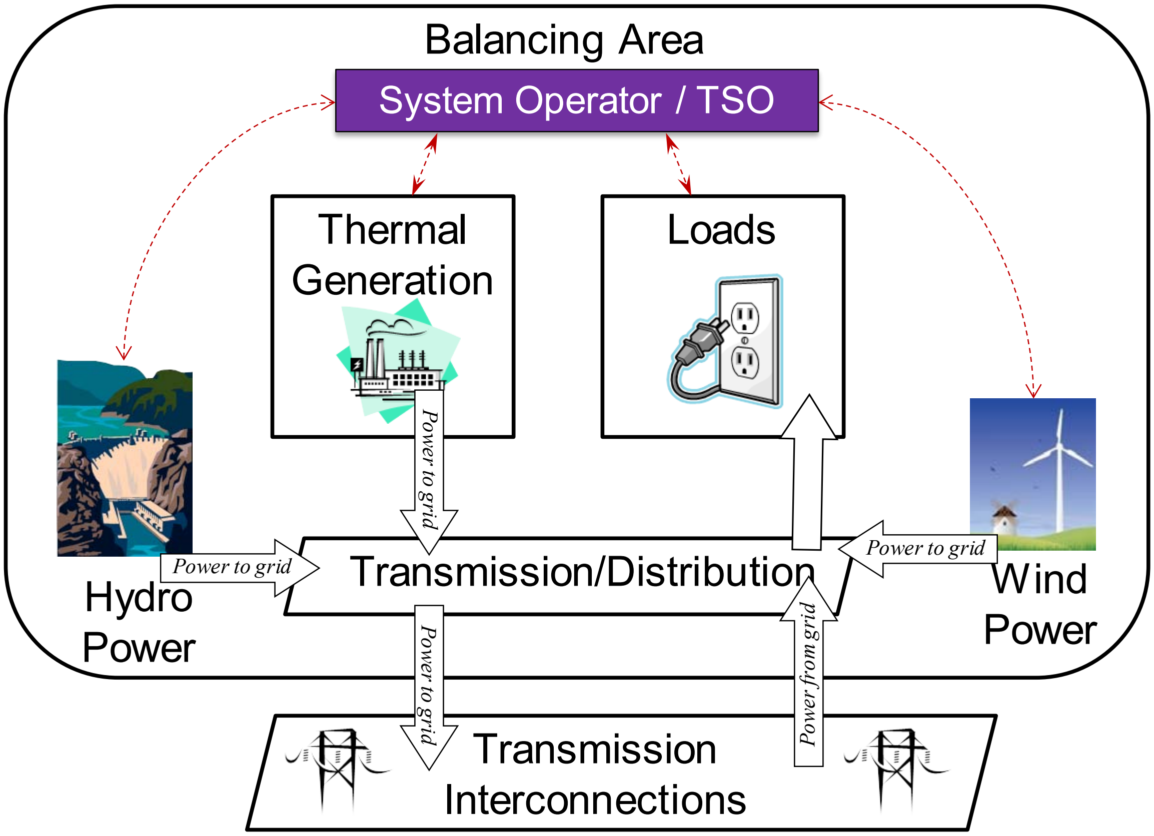

Figure 44. A practical configuration for wind and hydropower integration (note the red dashed lines in the figure refer to information flow including generation control signals) (Source: T. Acker presentation, Task 24 R&D Meeting #5, Québec City, Québec, Canada, June 2008)

[19] The obligation of a system operator is to balance net load with generation while honoring transmission constraints. Because variations in wind power production are generally uncorrelated with variations in load (as described in Chapter 2), it is not necessary to balance the variations of any single wind power plant, or any single load, but rather the aggregate of all loads net wind. This results in a lower overall requirement for balancing actions, and more effective use of available resources. Thus, no attempt is made to balance the output of one wind power plant using the resources of one hydro plant to produce a flat output.

5 Conclusions

Chapter 1 of this report introduced the aspects of electric system operation and planning that are of most relevance to wind integration: utilities and markets, ancillary services, and system planning and operation. It provided the vital background necessary to understand the reasons for forming Task 24, determine the objectives and questions being addressed, and present the members and work plan of the task. Chapters 2 and 3 went on to provide descriptions of wind power and hydropower, respectively, discussing the aspects of importance to the Task 24 objectives and expected results. Chapter 2 presented a perspective on the value of wind energy, then went on to describe in detail the characteristics of wind power variability and uncertainty, its contribution to system capacity, and their relationship to power system operation and planning. Chapter 3 provided an overview of hydropower, and then discussed in detail aspects of hydro system operation and planning of relevance to electrical system operation and planning. Of particular importance were aspects of hydropower of importance to wind integration. This chapter concluded with a summary of issues related to hydropower as a balancing resource and for energy storage. Next, Chapter 4 described power system operation and balancing in systems with wind power and hydropower, drawing upon the case studies and other relevant literature. The results of the participant case studies, in particular, were described in detail in this chapter with reference back to the questions posed when Task 24 was formed. It is the purpose of this chapter to summarize and present the conclusions of the task and suggested future directions for the study.[20]

At the end of Section 1.2, a set of questions were presented that motivated the formation Task 24 and led to the objectives and expected outcomes of the task. These questions are repeated below because they create a convenient framework for summarizing the conclusions:

- *Grid Integration Impacts and Costs*: What is the impact of wind power on the power system balancing area, and specifically, the ancillary services/reserves required; long-term system planning (capacity value); and transmission system (e.g., scheduling bottlenecks, etc.)? What are the appropriate study methods?
- *Hydropower Impacts*: What impact will provision of these ancillary services have on the hydropower system? Impacts include those on the physical resources (e.g., operations and maintenance); operational flexibility; and hydro system priorities (e.g., meeting flow constraints, satisfying environmental regulations).
- *Economics*: What is the overall economic value of wind energy in the hydro system? What "opportunity costs" are incurred for the hydro system in providing ancillary services to wind power (thus not being available for scheduling), and what are the economic benefits/opportunities in doing so? What is the effect of market configurations and system operation (e.g., scheduling intervals)? Are there wind/hydro "products" that can be of value both to power customers and hydropower providers (e.g., energy storage and redelivery)?
- *System Configuration*: Based upon the answers to the questions above, what are practical configurations for integrating wind and hydropower?

[20] At the final R&D meeting of Task 24, participants decided not to extend the task, but rather to continue addressing the questions posed in forming the task and furthering the analyses conducted in the case studies through participation in IEA Wind Task 25.

A summary of conclusions drawn related to each of these topics are provided below.

5.1 Grid Integration Impacts and Costs

Data presented in Chapter 2 provided a sense for the order of magnitude and frequency of power output changes with which a system operator or planner must deal. The data suggested that there will be a relatively small impact at the regulation (minute-to-minute) time scale, but becoming considerable at the hourly time scale and beyond (e.g., load following, unit commitment, reserve requirements), especially at high levels of wind penetration. In addition to being variable, wind power is also uncertain, and though accurately predictable much of the time, can suffer from large forecast errors that may occur at inopportune times during system operation. Wind power, while primarily an energy resource, does have a capacity value that should be considered in system planning. What makes wind power different to a system operator and planner as compared to other power resources is its variability and uncertainty, and learning how to understand and work with these characteristics. The overall impact of the wind power variations, forecast errors, and their associated integration cost—combined with the cost of wind energy, its marginal value, and the positive benefits it brings to the electrical system—depend on a host of factors including the system load, the generation fleet, operational and market flexibility, etc., and can only be accurately estimated via a thorough simulation of the power system. Several case studies of this task addressed wind integration impacts and costs, the relevant conclusions of which are summarized below.

- Finnish Case Study #1: This study showed that even with the limited flexibility of hydropower (run-of-the-river with small reservoirs), a large part of wind power forecast errors can be provided for by shifting hydropower back and forth inside 1 day. The study also showed that when correcting the forecast errors of wind power at a large balancing market in which hydropower produces most of the balancing (like in Nordic countries), there is not a great benefit of combining/integrating wind power and hydropower at a single producer. It is more cost effective to bid all flexibility of hydropower to the balancing market and use it from there to correct the system imbalances than to use it for dedicated balancing of wind power.
- Finnish Case Study #2: The study analyzed wind power energy penetrations of 10%, 20%, and 30% in the Nordic system (74,000-MW peak load), with the intention of determining whether or not there is enough regulation available from the hydropower to deal with wind power variation and forecast errors. The study identified a practical system configuration of 60% of electricity from hydropower, most of which being reservoir hydropower, and 30% of electricity from wind power. Results showed that a large part of hydropower capacity should be capable of flexible operation and able to provide the additional regulation required due to the high penetration of wind power.
- Norwegian Case Study #1: This case study presented a regional power system with an assumed 420-MW power transfer capacity. With regard to integrating wind energy, the most conservative approach allows for only 115 MW of wind power in the constrained network with 420 MW of capacity, as this will not require any control actions even in the very unlikely case of maximum wind and hydro generation (115 MW + 380 MW) at the same hour as the historically lowest consumption (75 MW). The results of the study showed that for the specific system under consideration, up to 600 MW of wind power is possible—without noticeable reduction in income from energy sales compared to an ideal non-

congested case—by applying coordinated operation of the wind power and hydropower plants.

- Norwegian Case Study #2: This case study considered the impact of wind power on system adequacy, assessed using data from a real-life, regional, hydro-based power system. Three cases were considered: the installed wind power is 62 MW (Case B) and 1,062 MW (Case A and Case C), which correspond to wind power penetration levels of 1.6% (Case B) and 28.1% (Case A and Case C). The annual load is 21,024 GWh, which gives wind energy penetration levels of 0.9% (Case B) and 15.2% (Case A and Case C). The study concluded that wind power will have a positive effect on system adequacy in a regional hydro-based power system. Wind power contributes to reducing the loss of load probability and improving the energy balance. Adding 3 TWh of wind or 3 TWh of gas generation are found to contribute equally to the energy balance, both on a weekly and annual basis. Both wind and gas improves the power balance. The capacity value of gas is found to be about 95% of rated, and the capacity value of wind about 30% at low-wind energy penetration and about 14% at higher wind penetration.
- Swedish Case Study #2: The aim of the simulation in the second Swedish case study was to study the possibility of balancing wind power in northern Sweden using hydropower in northern Sweden. The simulation included a total installed capacity of 795 MW of wind power, and that output was scaled to 1,000; 4,000; 8,000; and 12,000 MW. All hydropower stations larger than 10 MW in the studied area were considered (i.e., 154 hydropower plants with a combined capacity of 13.2 GW, which corresponds to about 80% of the installed capacity of all hydropower in Sweden). The conclusion of the study was that the existing hydropower in northern Sweden has sufficient installed capacity and is fast enough to balance even large amounts of wind power. The model predicted spill to occur, but that to an overwhelming extent such a spill can be avoided by using efficient tools for especially the season planning. Only in a few cases—and then, in particular, for a wind power expansion of 12,000 MW—will there be spill that depends on insufficient balancing capability in the hydropower.
- U.S. Case Study on the Missouri River: The case study on the Missouri River analyzed wind integration into the balancing area operated by WAPA and supplied by hydropower facilities located along the Missouri River. This study considered integrating five levels of wind power penetration of 3%, 3.7%, 9.3%, 18.6%, and 37%. The hydropower capacity is 2,400 MW from six hydro facilities containing multiple years of water storage, and the peak system load was 2,700 MW. The statistical study concluded that in the WAPA system, significant operational impacts from wind energy—those that must be dealt with in planning and operation (regulation, load following, system ramping of net load)—will likely arise when the wind penetration approaches 500 MW (about 18% of the peak system load).
- U.S. Case Study Sacramento Municipal Utility District: This case study focused on hydropower resources along the upper American River and operated by the Sacramento Municipal Utility District. Hourly simulation cases were completed for at least one full year of data for four proposed wind generation penetration levels: 102 MW, 250 MW, 450 MW, and 850 MW. These correspond to the following wind penetration levels (computed by dividing wind capacity by system peak load): 2.7%, 6.7%, 12.1%, and 22.8%, respectively. The study found lower penetrations of wind generation have only a small impact on fast

regulation requirements, but begin to dominate as the penetration increases. Wind integration costs were computed to range from about $2–8 USD/MWh of wind energy produced. The results show a very substantial reduction in operating cost and integration costs with the hypothetical Iowa Hill pumped-storage facility operating (as much as $5 USD/MWh). Furthermore, the results also show that integration costs decrease with increasing diversity of wind generation assets.

5.2 Hydropower Impacts

The material presented in Chapter 3 described the salient aspects of hydropower generation relevant to wind and hydropower generation. The type and magnitude of ancillary services and reserves that can be provided by a hydropower plant depends on whether it possesses significant storage or if it is a run-of-the-river plant with limited storage. The flexibility of operation also depends on whether or not the hydropower is part of a cascade of dams on a river system, and the level of coordination between those on the same river. Hydro facilities often have numerous functions—power generation being one—that guide their operation and define their flexibility. Layered on top of the physical and functional planning, there may be numerous organizations and stakeholders involved, along with differing market or economic situations. It is the interaction of the many functions, system configurations, and stakeholders that establish the authority, priority, and economics that govern the potential for wind and hydro integration.

The overarching question for studying wind and hydropower integration is whether system-operating impacts due to wind power can be accommodated by hydropower within the constraints on hydropower currently in place (or not easily changed), and in an economically advantageous way. And if so, what changes will this cause to hydropower operations or costs? In concept, hydropower should be able to provide short- to medium-term buffering of the enhanced variability and uncertainty wind power induces in the overall load net wind. Adding wind power to the system may or may not help hydropower meet power and other system demands, and the influence on other hydro functions, such as water deliveries, must be considered. That said, even within the constraints currently imposed on hydropower, it is a valuable system balancing resource, and possesses the inherent qualities needed to facilitate wind integration. Five of the case studies of this task addressed hydropower impacts, the relevant conclusions of which are summarized below.

- Australian Case Studies #1 and #3: Hydro Tasmania's system was modeled with 1,850 MW of peak load; a 900-MW minimum load; 2,267 MW of hydropower; and 630-MW/480-MW export/import capability via an HVDC interconnect with the Australian mainland. The studies found that a high level of wind power can be integrated into the Tasmanian system, up to 1,300 MW, if the interconnect with the Australian mainland is used and if measures are taken to address low system inertia. The study also identified that commitment of additional hydro generators operating in either synchronous condenser mode or tail water depression mode can largely improve the integration of the wind generation in Tasmania and problems associated with low system inertia.
- Australian Case Study #2: With respect to reservoir storage, in the case of islanded operation of a Tasmanian power system, system storage is unable to effectively absorb all output from large-scale wind generation due to coincident of high winds and high inflows. There is an increasing negative impact on water storage as wind generation capacity is increased. Interconnecting to the Australian mainland, via the addition of the high capacity HVDC

interconnection, significantly increases the ability to integrate wind generation in Tasmania without a negative effect on the energy in storage.

- Swedish Case Study #1: The first Swedish case study analyzed the possibility of balancing wind power with hydropower plants located along one certain river. The amount of wind power studied extrapolated to a penetration in Sweden equal to 6.5–7.5 TWh/year, or 5% of total energy production per year. The results from the simulations indicate that Swedish wind power installations that generate about 2–2.5 TWh/year do not affect the efficiency of the Swedish hydro system. At wind power levels of about 4–5 TWh/year, it is estimated that the amount of installed wind power should be increased by about 1% to compensate for the decreased efficiency in the hydro system. At wind power levels of about 6.5–7.5 TWh/year, the additional wind power needed to compensate for loss of hydro efficiency is about 1.2 %, but this figure has to be verified with more extended simulations.
- U.S. Case Study Grant County PUD: This case study considered two hydropower plants located along the Columbia River and operated by the Grant County PUD No. 2. The levels of wind penetration considered were 12 MW (1.8%), 63.7 MW (7.8%), and 150 MW (18.6%), with each percentage computed as a percentage of peak load (including sales of energy). Study results for the 2006 data year suggest that the overall impact on system statistics for regulation and load following is quite modest, even at a wind energy penetration of 150 MW (~19% wind penetration by capacity). The small statistical impact suggests that, absent other constraints, the physical generation resources are sufficient to handle wind variability at this level. However, due to changes in the distribution of load following hourly changes, there are some potentially significant operational challenges in scheduling the resources without infringing upon system constraints. To address this, an hourly simulation was conducted using day-ahead wind power forecasts, revealing that additional instances of dipping into contingency reserves occur due to missed wind power forecasts, and that additional short-duration excursions below the minimum flow requirements (for fish survival) also occur. The increases, however, are only modest and many can likely be handled during the day of operation, though at some cost.

5.3 Economics

The wind integration and hydro system impact studies have demonstrated the technical feasibility of integrating wind power and hydropower, even in systems with either transmission or hydropower constraints. Beyond the technical feasibility, two case studies investigated whether or not integrating wind was practical from an economic point of view, or looked at the effect of wind integration on the market. These two studies represent a valuable contribution to the task, and are a good start in addressing the overall question of economic feasibility.

- Canadian Case Study: Natural Resources Canada conducted a study for a small public utility in the United States along the Columbia River that demonstrated that using wind power to address load growth is economically feasible. It was also shown that the hydropower resources available to the utility being studied were satisfactory to supply low-cost balancing resources. In practice, due to underproduction of the wind power plant, it was found that the wind power would not have been economically favorable without Renewable Energy Production Incentives.
- Finnish Case Study #2: The study analyzed wind power energy penetrations of 10%, 20%, and 30% in the Nordic system (74,000-MW peak load). Because old power plants were not

retired in the study, there were no problems with system adequacy. Balancing this amount of wind power was shown to be feasible, but it was determined that a large penetration of wind power in a hydro-dominated power system will lower the spot price of electricity dramatically, which creates a challenge to get new investments in the system. It is unclear whether this kind of system could arise based on the markets even if it would be the most cost-effective way to serve load from a system perspective.

5.4 System Configuration and General Conclusions

As the breadth of the case studies indicate, integrating wind and hydropower can be quite complex. A summary of some key observations and conclusions from the work of the participants are provided below:

- Wind and hydropower are system resources that help serve the load via the transmission grid, and they are each controlled by the TSO. Addressing the incremental impacts of wind integration should be done in the context of the entire system, with all of its load and generation resources, and not in isolation from them (i.e., not one wind power plant balanced by one hydro plant to produce a flat output).
- When addressing wind integration, one should consider the holistic impact of wind power on the system (e.g., a cost-benefit analysis directed toward the electricity customer and effect on transmission system reliability), and not just the enhanced balancing requirements due to wind power's variability and uncertainty (e.g., wind power will enhance balancing requirements and incur an "integration" cost; however, at the same time the overall cost of electricity to the consumer may decrease due to wind energy displacing higher cost generation resources).
- The setup and operation of the transmission system and balancing area authority will have a profound impact on the ability to integrate wind power and the integration costs incurred. TSOs where the timing of transactions (committing units, buying and selling of electricity, ancillary services, and reserves) is frequent are more capable of integrating wind power and at lower costs.
- Transmission interconnections are important as they can limit wind and hydropower integration due to transmission constraints or congestion, or facilitate integration via power exchanges with neighboring systems. Larger balancing areas can more easily integrate wind and hydropower.
- Electrical systems can function within liberalized electricity markets, via a vertically integrated utility that participates with neighboring systems via bilateral transactions, or some combination of the two. Wind integration costs and impacts tend to be reduced in market systems, especially those with many market actors and flexible resources.
- The wind/hydro case study results were consistent with other wind integration studies in that the presence of an efficient and liquid electricity market has a large positive influence on the economics, frequently dominating all other factors. Furthermore, an important factor in interpreting the economic consequences of integrating wind and hydro is the perspective taken by the study: for the overall benefit of the electric customer vs. a single actor in the market (e.g., a utility, a wind developer).

- In conducting wind integration studies, the modeling assumptions and techniques can have a significant influence on the results. Therefore, these should be well-specified and understood when interpreting results and comparing different studies. Wind integration studies often involve the use of production cost models that simulate hourly operation of the power system. General production cost models (those not specifically developed for or by a hydropower-dominant utility) need improvements in how they model hydropower operation, water balances, and constraints, in order to better investigate the nuances of wind and hydro integration (e.g., the impact of enhanced system balancing requirements on hydro system constraints, or the ability to model the constraints). Virtually all production cost models require further improvement in how they handle wind power and wind power forecasts.
- At low wind penetration levels (~1%), wind integration impacts and costs are very minor. These transition to more cost and complexity as penetration levels increase to ~20%. Beyond ~20%, changes in system operational practices are likely necessary to optimally integrate wind and hydropower (e.g., use of advanced wind forecasting models incorporated into system planning). Islanded or small power systems with weak interconnections may more readily experience the effects of the enhanced variability in net load and increased reserve requirements caused by wind integration, including impacts on system inertia, and require attention in system planning.
- Non-power constraints on the hydropower system can influence the ability to integrate wind and hydropower. Such constraints may include higher priority functions of the hydro facility that dictate how water is run through the generators, such as irrigation water deliveries; environmental regulation (e.g., fish passage); recreation; or flood control. While these non-power constraints are important, they frequently occur on time scales of system operation different than those related to wind/hydro integration. Therefore, they do not tend to be prohibitive and often may not significantly influence wind and hydro integration, although at times they do reduce hydro system flexibility. Of the Task 24 participants, these constraints only played a significant role in hydro systems in the United States.

In summary, while hydropower systems possess special characteristics and operating constraints, the inherent flexibility of their generators and the potential for energy storage in their reservoirs make them well suited to integrate wind into the power system. From an overall perspective, wind integration into systems with hydropower is similar to wind integration into any power system: hydro resources are employed to meet net load much as they would be deployed to meet load alone. The fundamental difference with hydropower, as compared to other generation resources, lies in its flexibility. Hydro generators themselves are agile and quick responding; however, the use of hydro can be constrained by many other factors such as institutional constraints, resource availability, reservoir limitations, environmental restrictions on flow, etc. Therefore, when contemplating integrating wind into systems with hydropower, understanding the key factors constraining hydro and how they influence system flexibility is important. As demonstrated by the several case studies undertaken as part of this task, even amidst significant constraints, systems with hydropower resources are capable of wind integration. The primary advantage of hydro in integrating wind is its potential to provide ancillary services at a cost less than that of thermal resources.

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Appendix A: Bibliography of Reports

This appendix presents an extensive list of reports regarding wind integration. This list includes all reports cited in the body of this report plus others that may be of interest. The reports are organized alphabetically by country of origin. (Source: Northern Arizona University)

Country/ continent (leading author)	Topic	Reference	Link
Belgium	Wind Integration	Di Marzio G, Fosso O, Uhlen K, Pálsson M P, *Large-scale wind power integration - voltage stability limits and modal analysis*, 15th Power System Computation Conference, PSCC 2005, Liege	
Belgium	Distributed Generation, Wind Integration	Luther, M. *Grid operation and management with large scale wind generation,* European Conference on Integration of Renewable Energy Sources and Distributed Generation in Energy Systems, Brussels 25-26.9.2001	
Canada	Wind Integration, Energy Markets	AESO, 2006. *Wind Integration Impact Studies. Phase 2: Assessing the impacts of increased wind power on AIES operations and mitigating measures*.	
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Canada	Wind Integration, Wind-Hydro	Benitez, Liliana E.; Benitez, Pablo C.; and van Kooten, G. Cornelius, 2006. *The economics of wind power with energy storage*, *Energy Economics* 2007, doi:10.1016/j.eneco.2007.01.017.	www.elsevier.com or at www.sciencedirect.com
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Canada	Wind Integration, Wind Power Variability	Wang, Rui and Baker, David 2005. *Alberta Wind Power Variability Study*, Alberta Electric System Operator, Calgary Place 2500, 330 – 5th Ave. SW Calgary, AB T2P 0L4, July.	www.aeso.ca/files/WindVariabilityFinalReport.pdf
Canada	Wind Integration	*Maritimes Area Wind Power Integration Study Summary Report*, 2007, NBSO Wind Project	
China	Wind-Hydro	Yanfang, F., Yibo, W., Qin, C. *Wind-Hydro Hybrid Power System Stability Analysis*. Xinjiang University	
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