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THE ECONOMICS OF WIND ENERGY

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COLLECTION OF PAPERS

FOR DISCUSSIONS

MASTER

Edited by Harri Vihriälä,
Finnish Wind Power Association

IMATRAN VOIMA OY

DISCLAIMER

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A Word from Editor

Dear Participant of "The Economics of Wind Power"-conference,

Here are the papers to be presented on conference, which were sent to us in time. They are now copied for You to serve as basis for discussion. As organizers we decided to experiment with a new kind of conference, which is based on panel discussions. All the authors are given an opprtunity to oral and poster presentation. On all sessions, there is an invited keynote speaker, who helds a longer introduction from the subject of the session. Then all the participants of the sessions are given 3-5 minutes to present their wiews shortly and rest of the session is devoted to panel discussion.

This type of conference demands more from all of the participants, but it is also more rewarding. Please become briefly familiar with materials of each session beforehand to have the maximum benefit. You may also prepare some questions from the points, which have remained unclear to You and write them down for the discussion. Oppoturnities to mutual discussions with speakers and other participants are provided on panel sessions on Tuesday and Wednesday.

Unfortunately we could not receive all of the papers in time for this publication. Therefore we substituted these papers with corresponding abstracts. Papers successfully presented in conference will later be published in normal conference proceedings of higher printing quality.

I wish You rewarding and pleasent confererence on behalf of the organizers.

Mr. Harri Vihriälä, M. Sc. (E.E.)
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WIND ENERGY LOOKING AHEAD IN ANDHRA PRADESH (INDIA)

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ABSTRACT :

Wind activity is catching up very much in India. Andhra Pradesh, a state in southern part of India is poised to set up large Wind Farms . Based on Wind mapping studies, some areas of Anantapur, Cuddapah, Kurnool and parts of Nellore and Chittoor Districts are found to have good wind potential.

Some of the potential wind locations identified in the state are : Ramgiri, Singanamala, MPR Dam (Anantapur Dt.); Payalakuntla (Cuddapah District), Narasimhakonda (Nellore District), Kakulakonda and Narayanagiri (Chittoor Dt.). Already 1.1MW wind farm is in operation in Tirumala and 2 MW demonstration wind farm in Ramgiri. The State Government has also accorded permission to several wind farm developers. The wind Farm capacity estimated at the above sites is about 284 MW. Details of the ongoing Wind Farm projects, estimated output at locations along with economics of power generation discussed in the paper.

ECONOMICS OF GENERATION OF ELECTRICITY BY WIND IN INDIA

ABSTRACT

Wind energy activity in India is expanding very fast. With the introduction of installed capacity of 3.3 MW during 1986, this has grown to about 250 MW by March 1995, next only to that in USA and Europe. The growth has been phenomenal after 1991 due to the entry of private entrepreneurs who have found that the investments in wind business is profitable and providing quick returns. The wind energy potential in India is estimated to be about 20,000 MW. The target of Ministry of Non-Conventional Energy Sources, Govt of India is 500 MW to be installed by March 97. However, the present trend in growth indicates that the actual installed capacity may exceed this target.

The investments in wind business is profitable in India due to various incentives offered by the Central as well as State governments. Major incentives by the Central government are :

a) Hundred percent depreciation on investment during first year.
b) No custom duty on the import of major components and spares.
c) Soft loan upto seventy five percent of the project cost from Central government funding agency of Indian Renewable Energy Development Agency.

The incentives offered by State governments vary, however the important ones are :

a) Wheeling and banking of power through State electricity grid.
b) Selling of power to government or third party.
c) Capital subsidy.
d) Availability of land on lease for twenty years.
e) Sales tax exemption on the sales regular product, etc.

Taking into account various factors such as capital cost of installation of windfarms, depreciation benefit, availability of soft loan, sales tax benefit, income due to sale of power, availability of land on long lease, life of machines, O&M expenditure etc., it is shown that the cost of generation of electricity by wind is comparable to and is even cheaper than from conventional sources such as thermal power and the pay back period is about 5 to 6 years.

Sensitivity analysis has also been carried out, taking into account the variation in some of the parameters as mentioned above.

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ANNEXURE

Abstract of paper proposed to be presented by Padmashree Rakesh Bakshi, Chairman, RRB Consultants & Engineers Pvt. Lt. at the EWEA Special Topic Conference on the "Economics of Wind Energy" to be held on September 5-7, 1995 at Helsinki, Finland

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"The Economics of Establishing a 10 MW Wind Farm in Tamil Nadu, South India"

ABSTRACT

Compared to conventional sources of energy such as coal and diesel and also due to other factors such as short project gestation, modularity, non-polluting nature of the technology and present overall shortage of power and energy the demand of wind power projects by Private Companies is developing exponentially. In addition the escalating cost of conventional energy has also made private companies to look towards power generation from wind. The above referred paper proposes to provide an insight into the economics of establishing a 10 MW Wind Farm in Tamil Nadu, South India.

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Wind energy make difficult start in Estonia

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ABSTRACT: Economical calculations of the wind energy costs indicate the possibility to use wind energy in Estonian islands. The key question will be the financing of the wind energy programme.

1 INTRODUCTION

In recent years renewable energy sources have become an attractive energy producer in many countries. In Estonia the wind power seems the most interesting and promising. In spite of several good sites in coastal regions and especially in western islands Saaremaa and Hiiumaa, unfortunately occur some obstacles for wind energy development.

Situation in the Estonian electric power industry is very complicated today. During last years penetrate fall in electricity production and export to Russia gives reason for suspicion that leaders of energy are not enthusiastic in using of wind energy. Their principal statement is that wind energy has not priority like other energy kinds in Estonia. Therefore wind energy is not financed. Although installing of wind power stations in the Estonia and especially in islands is perspective, is unfortunately not possible to finance wind energy projects from state budget. Therefore in direct use of wind energy are interested some local organisations in Estonia. It is necessary before economic aspects become acquainted with wind condition in Estonian regions best suited to use wind power.

1.1 WIND RESOURCE

Best wind conditions lies in coastal areas of islands in West-Estonia. All island's Hiiumaa, Saaremaa, Kihnu and Vormsi have a normal local grid network. Connections with mainland are going on through cables in sea. Of the same value or even better is annual wind speed in islands Osmussaar, Vilsandi, Naissaar, Ruhnu, Pakri and Prangli. These islands have not connection with united grid. Island Vilsandi is a reservation of birds and using wind energy there is not possible. In any case the data of Vilsandi show a very good condition for using wind turbines in north-west and west coastal areas of Saaremaa. Necessarily rest places and air-routes of migrant birds must be taken into consideration. Data to be used in estimating the wind speed distributions are from 1946 to 1963 [1]. The annual wind speeds and height of measurement show Table I. Taking place measurements of wind speed in Tahkuna (Hiiumaa) and Osmussaar just now shows, that precise measurable annual wind speed really can be higher. Wind speed in 10 and 30 m high are calculated respectively with formulas $V_{H=10} = V_0 \cdot (10/H_0)^{0.16}$ or $V_{H=30} = V_0 \cdot (30/H_0)^{0.16}$.

The value of annual wind speed characterises wind resource by one-side. A frequency distribution of wind speed gives a better review about expedience of wind turbines using. Theoretical output of one good wind turbine, calculated by known data of wind speeds, cans help here. So calculated output of wind turbine Vestas V27-225 kW in site of meteorological stations shows Table II.

Table I

Location of meteorological station	Height of measure-ments H m	Annual wind speed V_0 m/s	Calculated wind speed $V_{H=10}$ m/s	Calculated wind speed $V_{H=30}$ m/s
Tahkuna	13	6.4	6.1	7.3
Vormsi	11	5.6	5.5	6.6
Pakri	13	5.6	5.4	6.4
Naissaar	13	5.8	5.6	6.6
Kihnu	13	6.2	5.9	7.1
Ruhnu	12	5.8	5.6	6.7
Sõru	13	5.8	5.6	6.6
Kuressaare	13	5.9	5.7	6.7
Sõrve	12	6.2	6.0	7.2
Raugi	13	5.3	5.1	6.1
Osmussaar	13	6.8	6.5	7.8
Vilsandi	13	6.5	6.2	7.4

Table II

Location of meteorological station	Calculated theoretical output of one Vestas V27-225 kW wind turbine, MWh		
	Winter	Summer	Year
Kuressaare	277.7	209.6	487.2
Vilsandi	364.1	255.9	620.0
Sõrve säär	329.8	215.9	545.7
Ruhnu	317.9	169.4	487.3
Sõru	267.4	189.8	457.2
Raugi	244.8	179.5	424.4
Osmussaar	422.8	249.8	672.6
Pakri	266.9	180.9	447.8
Naissaar	311.2	195.1	506.3

Table III

Location of meteorological station	Calculated 90 % output of wind farm with 16 Vestas V27-225 kW turbines, GWh/km²		
	Winter	Summer	Year
Kuressaare	3.998	3.018	7.016
Vilsandi	5.243	3.685	8.928
Sõrve säär	4.749	3.109	7.858
Ruhnu	4.578	2.439	7.018
Sõru	3.850	2.733	6.583
Raugi	3.526	2.585	6.111
Osmussaar	6.089	3.597	9.686
Pakri	3.843	2.605	6.448
Naissaar	4.481	2.810	7.291

The results in Table II are calculated by windspeeds at 10...13 m height. Therefore the realistic output can be greater. Winter period is from October to March and summer period from April to September. Source of power curve for Vestas V27-225 kW is [2]. Data in Tables I and II confirm expediency of wind energy use in Estonia. The annual medium wind speed is 5 - 6.5 m per sec at 10 m height. Calculated annual energy production for good windmills is 1800...2400 and more kWh per kW. The potential total annual output of wind energy produced by windmills extends up 6...8 millions kWh per square km (by 16 windmills, Table III).

1.2 FIRST WIND POWER PROJECTS

The Hiiumaa Centre for the Biosphere Reserve of the West-Estonian Archipelago is initiator of establishment the first Estonian wind power station Tahkuna in Hiiumaa North cape. It is a 150-kW wind turbine from Danish company GENVIND. The main investor of this project was Denmark Ministry of Environment. The groundwork was made with participation of local workers. At present time this wind turbine is installed, but not yet connected with electrical grid. Connection and testing will probably be finished in October 1995. Then appear also the total investment of this project. Accordingly to the plan of Hiiumaa Centre for Biosphere one GENVIND 20-kW wind turbine manufactured in Estonia will be located near the station in the future.

Autonomous wind-diesel power project in island Prangli consists of 150-kW Danish NORDTANK wind turbine, two 120-kVA Dieselgenerator, 80-kVA inverter/harger, 100-kW rectifier bridge and 384-V 680-Ah tubular type battery. Automatic station for recording of wind speed is in operating there. Finnish renewable state program NEMO-2, EC/PHARE, Danish Energy Ministry, Neste Oy, NORDTANK, Finnish Meteorological Institute and RISØ are taking part to finance this research. According to a plan the total estimated cost of this study is nearly 3.8 million FIMs. In this research-project from Estonian side take part also company Prangli Tuulejõud, Estonian Institute of Energy and Re-En Centre TAASEN.

One of possibilities to use wind energy in Estonia is apply the "second hand" wind turbines from Denmark. In this line develop activity Company Saare Tuuleenergia (Wind energy of Saaremaa island). In plan this company is to set up 2...5 Vestas 100...200 kW wind turbines in coastal area of West Saaremaa.

2. ECONOMICAL FACTORS

The current market price for electricity is now very low, about 2.3 ECU ct/kWh or 0.044 DM/kWh but presently can be advanced one and a half time in next 2...3 years. The cost price for electricity is six to seven times greater with Diesel generator in island Ruhnu today. The electric grid of Saaremaa, Hiiumaa and Muhu islands has set from manner through sea cables of 35-kV, user on Vormsi, Kihnu and Abruka islands by sea cables of 10-kV. Declared data of losses is over 20 % in grid of Estonian Energy System in 1993. That is out of proportion considering the production of electricity. This could enable to develop wind energy in the far end of the grid, in islands Hiiumaa, Saaremaa, Vormsi, Muhu and Kihnu.

2.1 EXAMPLE OF CALCULATION

An idea about economical factors of wind energy in local conditions can be obtained from Table IV in next page. Comparisons take place in this table of different sites by same wind turbine Vestas V27-225 kW. That is an example of possible distribution of investment and cost of electricity at partial use Estonian workers and organisations. Firstly the maintenance costs grow this smaller. The total costs and consequently also price of electricity can be considerably reduced by use of more windmills in the windpark. To cut down costs is possible with using domestic industry in manufacturing of tower, nacelle and other components of wind turbines, of course by co-operation with advanced foreign firms. Several companies in Estonia are occupied with manufacturing of components and boats from glasfibre

Table IV
ECONOMICS OF A VESTAS V27-225 kW WIND TURBINE BY VARIOUS SITES IN ESTONIAN ISLANDS
CALCULATED PRICE FOR WIND TURBINE IS 406250 DM (1806 DM/kW)

Site of meteorological station	Sõrve	Vilsandi	Kuressare	Tahkuna	Sõru	Vormsi	Raugi
Average wind speed in 10 m height	6.0	6.2	5.7	6.1	5.6	5.5	5.1
Annual production, MWh/year	545.7	620.0	487.2	582.8	457.2	467.6	424.4
Productivity, kWh/m²	952.4	1082.0	850.3	1017.1	797.9	816.1	740.7
Annual availability, %	27.7	31.5	24.7	29.6	23.2	23.7	21.5
Foundation (9 % of price), DM	36563	36563	36563	36563	36563	36563	36563
Installation, etc. (11 % of price), DM	44688	44688	44688	44688	44688	44688	44688
Total investment, DM	487500	487500	487500	487500	487500	487500	487500
Operation and maintenance cost:							
year 1-2, DM	9000	9000	9000	9000	9000	9000	9000
year 3-5, DM	12600	12600	12600	12600	12600	12600	12600
year 6-20, DM	45000	45000	45000	45000	45000	45000	45000
Middle maintenance cost, DM/year	3330	3330	3330	3330	3330	3330	3330
Lifetime, years	20	20	20	20	20	20	20
Bank interest rate, %	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Turnover tax, %	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest rate, %	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Annuity, 1/year	0.098	0.098	0.098	0.098	0.098	0.098	0.098
Investment cost, DM/year	47820	47820	47820	47820	47820	47820	47820
Total cost, DM/year	63937	63937	63937	63937	63937	63937	63937
Cost of electricity, DM/kWh	0.117	0.103	0.131	0.110	0.140	0.137	0.151

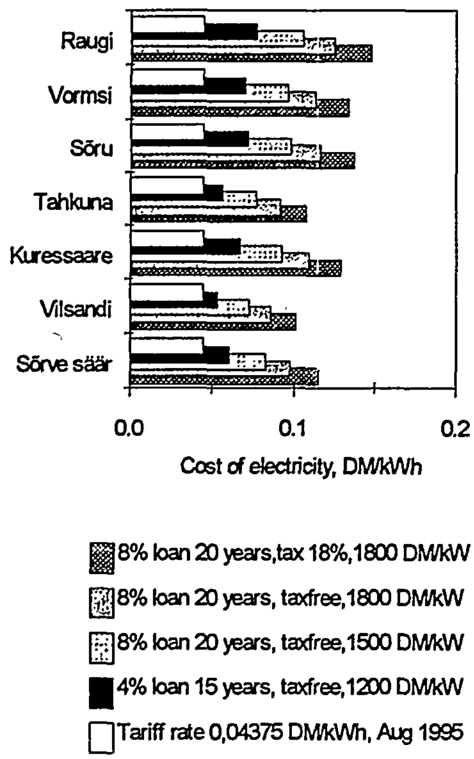

Fig. 1. Calculated reduction of costs depending on price per installed power and turnover tax in use windmills with characteristics of Vestas V27-225 kW in variable sites in Estonian islands.

for export goods. Some factories are able to produce tubular tower, etc.

2.2 FURTHER OBJECTIVE

Table IV illustrates a little bit the situation in Estonia, that is characterised by a lower pay and owing to this also low tariff rate of electricity. A low-percentage long-term loan is problematical without government subvention for wind energy. Already getting free from turnover tax can help, as you can see in Fig. 1.

Therefore it is very important to verify with a successful function of the first wind power stations the expedience and utility of the use of wind turbines.

Our economical calculations of wind energy costs indicate a possibility to use wind energy in Estonian islands. If we keep in view prognosis about 1.5 times increase in electricity selling tariff in the next 2...3 years, what is very likely, then a wide development of wind energy in Estonian islands in near future is only a question of investment.

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[2] RISØ. Technical specifications: Vestas V27 - 225 kW. Measurement summary No. 6.1, September 1989.

Status and Perspectives of Wind Turbine Installations in Italy

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ABSTRACT: The paper intends to illustrate the Italian situation in wind sector, giving some elements to explain why some delay is registered with respect to other European countries. Further than the present day situation, from which it can be concluded that the diffusion process is still commencing, being installed only 20 MW, the perspectives are discussed. Projects for plant installations totalling about 430 MW have been submitted to the electric utility. The actual realization of these important initiatives will probably depend on the ability to use wind energy as an occasion to sustain economic development of the involved zones.

1. Introduction

Up to now, wind turbine deployment has suffered some relevant drawbacks which left Italy among the last countries in Western Europe with regard to installed power. High population density, complex orography, availability of wind resource only in Apennines and, sometime, coastal zones caused a historical delay in the development of a national industry and diffusion of technology.
In the last few years, following the Parliament decision to strongly support rational use of energy and national sources, the joint effort of ENEA, ENEL SpA and industry led to the implementation of more suitable conditions for a significant diffusion of wind turbine technology.
As results, it is worth remembering the development of a national technology in the medium sized machines and a significant engagement for large size turbine development. At present two industries, the West SpA and the Riva Calzoni SpA, are able to offer quite reliable products. Moreover, the West SpA is developing the 2 MW Gamma 60 turbine, relying on the introduction, by utilities, of wind energy into electric energy mix.
Concerning siting, a detailed territory monitoring has allowed the individuation of suitable areas, both with respesct to wind speed and to absence of territorial constraints. The most important zone is an actual "wind pole" in the Apulian Apennines. Finally, legislative measures recognize, now, environmental benefits related to this source of energy. At present, an energy tariff of 164.4 Italian Lire/kWh is acknowledged for the first eight years and 78.8 Italian Lire/kWh for the remaining lifetime. Besides, many regions are introducing wind energy in their own energy plans, providing for financial supports on investment costs.
As overall results, though at present time the installed power is only around 20 MW, many requests for grid connection have been presented by private investors to national utility, amounting to about 360 MW at the end of 1994.
Some months will be needed in order to assess the actual implementation of these very significant projects.

However, it is out of question that wind energy is crossing a period of promising growth and many enterpreneurs judge that the conditions are going to be favourable for investment in the wind sector.

2. The boundary conditions and the present situation

In Italy wind energy has been considered as an integrative option to be included into the mix for electricity production during the 'eighties. Many operators were involved in order to create a seasonable context for wind energy exploitation. Therefore, a joint effort among ENEA (the National Agency for New Technology, Energy and the Environment), ENEL SpA (the utility company) and industries started, with the aim of developing a suitable technology and finding proper sites for plant installation.

The availability of medium size technology, the anaemological characterization of more than 200 sites and the development and experimentation of an advanced large size turbine can be considered as the main results of the activities.

In the meanwhile, also the institutional conditions changed in order to favour wind energy diffusion. First, the 1988 National Energy Plan indicated as target an installed power ranging from 300 to 600 MW by the year 2000. Then, since the promulgation of the law 9 January 1991 n. 9, autonomous producers were allowed to build and operate renewable based plants and sell electricity to the national grid. The law 9 January 1991 n. 10, would provide for contribution on wind farms investment cost ranging from 30 to 65 %, though this law did not find application because of lack of funds. Very likely, however, the most effective initiative has been the directive 29 April 1992 n. 6, promulgated by the CIP (Comitato Interministeriale Prezzi): this legislative measure established new tariffs for renewable source derived electricity: in the case of wind energy, the tariff was fixed to 150 Lire/kWh over the first eight years and 72 Lire/kWh for the remaining lifetime. These figures, revised year by year according to inflation rate, are now closed to 164.4 e 78.6 Lire/kWh.

Table I reports the main data concerning plants in operation at the end of 1994. As better arguable also from Fig. 1, in practice wind turbine installations started in the 1991 at experimental level, with the testing of national and foreign machines and, in any case, with public support on investment. In any case, one can state that wind turbine diffusion is going to start now.

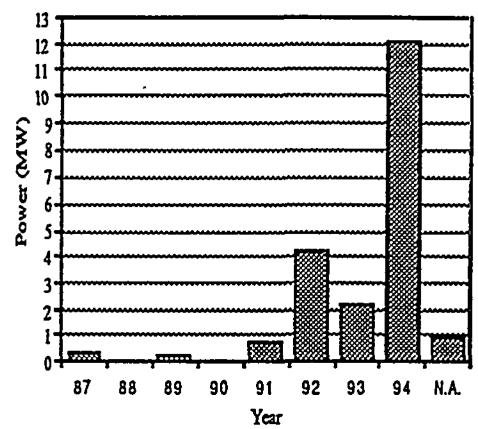

Fig. 1 - Wind power installations by year

However, some lessons have been learned during these years.

First of all, Italy does not lend itself naturally to wind energy exploitation. From the European Wind Atlas it can be argued that, in the same topographic conditions, the Italian most windy areas offer the same producibility of the English less windy areas!

Moreover, high population density, complex orography, wind availability mainly in coastal and mountain zones, many kind of territorial constraints (mainly in coastal and mountain zones!), make quite difficult to meet all conditions for plant installation and bring into effect projects, even when set up by public bodies. So, first constructional experiences performed by ENEL, both in mountain and marine environment, evidence the lack of certain procedures for plant authorization. For instance, ENEL reports [4] that the construction of

Acqua Sprruzza test site, in Molise Region, required quite a number of permits - involving many aspects and different institutions and obtained over a three years period - concerning, among the others, environmental impact, military, seismic and hydrogeological securities.
The above cited case - and some others similar - is likely to indicate that one of the most serious drawbacks is given by the suspicious approach of local populations.
In fact, state policy, drived by general interests - like global environmental impact, necessity to exploit a national, inexhaustible source and cut down energy import - conflicts with local populations approach, which still ascribe scarce value to global advantages, while worry very much about local advantages and disadvantages, according to the well known "why in my back yard?" syndrome. Thus, people give importance to environmental aspects like noise, visual impact, land destination and occupation, impact on avifauna.
But, on the other hand, they are also very sensitive to some possible social profits, mainly when related to local economy and employment growth.

3. The perspectives

Though with some years of delay, Italy will probably follow other European countries with respect to wind energy diffusion. In fact, the concurrency of availability of suitable sites, acquired technological maturity of wind turbines, and adequacy of tariffs have raised the interest of public and private bodies. Some Southern regions, where the wind resource is more considerable, are including wind energy into their own energy plans and foresee support for diffusion. Requests to the electric utility - sent in by many developers and aimed at obtaining permission for connecting wind farm to the electric grid - have dramatically increased. As far as June 1995, requests totalling about 430 MW, to be realized in the years ranging from 1995 to 1999, have been submitted to the electric utility ENEL. This figure is like to increase in next years. Now: further than technical and economical parameters, like wind speed, tariffs and investment costs, what elements will influence the actual implementation of these initiatives?
Probably, financial and social aspects will be of capital importance. Concerning financial aspects, wind energy - as well as all renewable energies - is capital intensive. On the other hand, national operators have still scarce experience in wind farm financing, construction and operation: credit institutions can hardly evaluate projects and, in addition, national developers must increase their credentials. In this phase, the presence of foreign credit institutions and wind farm developers could help the overcome these difficulties.
Further interesting considerations on social aspects arise from the analysis of grid connection requests. Fig. 2 shows the distribution of power to be installed by province.

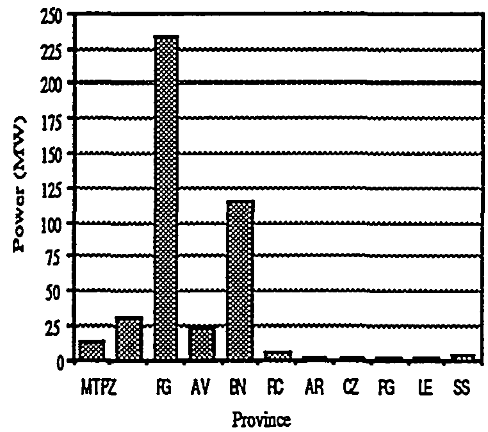

Fig. 2 - Request of grid connection at mid 1995 by province

It can be seen that about 95% of power regards few provinces, and, as better illustrated in Fig. 3, individuates a quite small zone - having an area of about 4000 km^2 - in the Appeninnes between Apulia, Basilicata and Campania (N.B.: the zone incude the province of Beneventum, which roughly means "goog wind"; Romans called that province Maleventum, i.e. "bad wind", and changed the name in

Tab. 1 - WIND TURBINE GENERATORS INSTALLED IN ITALY (AT 30 DEC. 1994)

Site	Operator	Grid Connection	Number	WTG TYPE	WTG POWER (KW)	Rotor Diameter (m)	Tower Height (m)	Plant Power (MW)
Alta Nurra	ENEL S.p.A.	Nov. '89	1	M30	200	33	33	0.20
		Apr. '92	1	MEDIT I	320	33	26	0.32
		Mar. '91	1	MS-3	300	33	25	0.30
		Apr. '91	1	WD34	400	34	32	0.40
		May. '92	1	GAMMA 60	1500	60	66	1.50
Bisaccia	WEST Regione Campania	Jan. '92	4	MEDIT I	320	33	26	1.28
		Apr. '93	2	MEDIT I	320	33	26	0.64
		Jan '92	3	AIT-03	30	10	12	0.09
		Apr. '93	13	AIT-03	30	10	12	0.39
Palena (Sangro)	Consorzio Bonifica del Sangro	Feb. '94	3	MEDIT I	320	33	26	0.96
		Feb. '94	1	VESTAS V27	220	27	31	0.22
		Feb. '94	1	VESTAS V20	100	20	24	0.10
Villagrande	Comune	Apr. '93	2	MEDIT I	320	33	26	0.64
Acqua Spruzza (Frosolone)	ENEL S.p.A.	Wint '94	2	M30	200	33	33	0.40
		Wint '94	2	MEDIT I	320	33	26	0.64
		Wint '94	2	MS-3	300	33	25	0.60
		Wint '94	2	WD34	400	34	32	0.80
Frosolone	Comunità Montana Sannio	'94	1	MEDIT I	320	33	26	0.32
Oristano	Consorzio Industriale	May. '92	1	MEDIT I	320	33	26	0.32
Carloforte	N.D.	jun. '94	3	MEDIT I	320	33	26	0.96
Monte Uccari (Nurra)	Consorzio Bonifica di Nurra	Wint '94	5	MEDIT I	320	33	26	1.60
San Simone (Nurra)	Consorzio Bonifica Sardegna	Jan. '93	1	M30	200	33	33	0.20
Brunestica (Nurra)	Consorzio Bonifica di Nurra	'94	3	MEDIT I	320	33	26	0.96
Tocco da Casauria	Comune	Jun. '92	.2	M30	200	33	33	0.40
Campanedda	Consorzio Bonifica di Nurra	'94	4	M30 A	250	33	33	1.00
Ottava	Consorzio Bonifica di Nurra	'94	4	M30 A	250	33	33	1.00
Villacidro (CA)	Consorzio Industriale	N.A.	4	HMZ Windmaster	150	21.8	23	0.60
		Spr. '87	2	HMZ Windmaster	160	21.8	23	0.32
Villa Favorita	Società Villa Favorita	N.A.	1	HMZ Windmaster	150	21.8	23	0.15
Frontone (PS)	ANAS	N.A.	1	Leroy Sonas LS PL 315	216	N.D.	N.D.	0.216
Collarmele (AQ)	Marsica Gas	Jul '93	1	Riva M30 A	250	33	33	0.250
Ostuni (BR)	Massari V.	Apr. '92	1	N.D.	150	N.D.	N.D.	0.150
Assemini (CA)	CO2 Industriale	Oct. '92	1	VESTAS 227	225	27	31	0.225
Casone Romano (FG)	Local	Dec. '94	10	M30A	250	33	33	2.5
						TOTAL		20,7

Fig.3 : THE CAMPANIA - APULIA WIND ENERGY BASIN

ITALY : 430 MW

CAMPANIA-APULIA BASIN : 402 MW

Beneventum following an important victory in war).

This zone is also marked by depressed economy, high unemployment and emigration rates.

The large amounts of initiative in that zone can represent the occasion to meet two scopes: first, to favour the exploitation of a national energy source; secondly, to stimulate local economy and employment.

Consequently, industrial operators and some local authorities are moving in order to look at wind as an actual economic resource for local populations, whose exploitation can turn into account lands not suitable for other uses, and play an important role for sustaining economic and social development, so overcoming the above discussed mistrust of local populations.

Considering the large potential available in the mentioned restricted zone, the following actions are considered to meet the cited objectives:

-transferring "in loco" some parts of turbine productive process;

-formation and use of local firms for civil and electric works;

-formation of local competences for operation and maintenance;

-making compatible wind farms with other economic activities;

-realization of infrastructures like roads, electric and telephone equipments and lines, which can sustain other economic activities;

-touristic exploitation of renewable plants, in connection with the environmental and hystorical resources, considering both wind farms and photovoltaic plants (N.B.: the 0.6 MW Delphos photovoltaic plant is located near Manfredonia, in the neighbourhood of the area interested to the constitution of the wind pole; the 3.3 MW Serre photovoltaic plant is installed not so far).

If this approach success, wind energy will largely diffuse in Italy and the target established by the 1988 National Energy Plan target will be met.

THE ECONOMICS OF WIND ENERGY
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ECONOMIC AND FINANCING ANALYSIS FOR FAVOURABLE WIND SITES IN ROMANIA

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ABSTRACT

The most favourable wind sites in Romania totalize almost 600 MW installed power onshore and up to 2000 MW for the Black Sea shallow offshore, with 5 x 10^9 kWh/year presumed output.

The sites, according to their resources and their economic efficiency, are classified in order as follow:

- Black Sea shallow offshore up to 5 m depth, area where the utilization of the harbour dikes is primary;
- high mountain areas;
- hilly and plateaus areas;

In Romania the most efficient site from the analyzed ones is the North dike of Constanta harbour that allows up to 5 MW installed power with 12 x 10^6 kWh/year output power, at a price of only 0.058 $/kWh.

The other sites could insure output power at prices from 0.06 $/kWh up to 0.111 $/kWh.

In the existing conditions, with no sustain in the Romanian legislation for the renewables (like subsidies, environmental taxes or credit quaranty), the economic presumed results are promising taking into account that the CoE for some retrofitted thermal plants is 0.04-0.08 $/kWh over the reference cost and for the new hydro projects is expected to be 0.1 up to 0.666 $/kWh.

The necessary investments for the 15 analyzed wind farms with 2578.5 MW total installed power is up to 4.5 x 10^9 US $ with a specific investment of almost 1700 $/installed kW.

Consideration Concerning the Costs of the 300 kW Wind Units Developed in Romania

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ABSTRACT: A demonstrative wind farm with four research units, 300 kW each, is in developing stage in Romania. The paper shows economic analysis of these experimental wind units and their cost structure focusing in component costs, performance, manufacturing technology and installing work.

1 INTRODUCTION

The european message regarding the windfarms development has been received in Romania in 80's. An interdisciplinary research group from the western zone of the country initiated in 1982 a research program for a mountain site in Banat Mountains. At this program, developed relative slowly but though continuous, takes part Technical University of Timisoara, a few designing institutes (HIDROTIM S.A., IPROTIM) and a lot of companies (STEEL CONSTRUCTION S.A. Bocsa, RENK Resita, EOL Targu Mures, ELECTROMONTAJ Timisoara. RENEL Resita, etc.).

Semenic Mountain, which is considered a potential site for an industrial windfarm, is placed in the west of Romania-Caras Severin district, near a strong industrial center named Resita which has more than 300 years of tradition. It has an area of 1180 km² between 45° 00' and 45° 23' north altitude, respective 21° 58' and 22° 18' eastern longitude [1]. In the zone of higher altitudes (peaks Gozna Stone-1447m, Semenic-1446m, Nedeia Stone-1437m) is stretching a rock plateau about 5 km² type "alpine desert" that permit to organize a windfarm composed by 330 wind units having the unitary power of 300 kW, and totaled about 100 MW. The multiannual average wind speed at 30-40m level being 8 m/s. is a "very good" site [2]. Annual output of the windfarm will be about 750 Mwh/year.

The area is hydrological and hydroenergetical arranged through interesting workings, a part of them older than 100 years, which are useful for the water and energy needs of industrial center Resita. Windfarm participation, especially in winter, will be able to improve the efficiency in this way.

The windfarm achievement depends on the offer of capital which in Romania is very low. Therefore the present achievements is limited at four experimental research wind units that are erected upon the Semenic site. They can represent the first units of a demonstrative windfarm, in which we will agree the presence of some european wind units [3] adjusted for the alpine climatic condition (humidity, white frost, atmospheric electric discharges).

2 FOUR 300 KW EXPERIMENTAL WIND UNITS

Upon the Semenic site in the last 10 years have been erected 4 wind units each of 300 kW, designed as experimental units, financed by the state into the frame of some research & development programs. The program being initially in a period of economic isolation of the country, the units achievement it was made exclusively through internal effort. Limited funds and indecision of official bodies concerning the energetic strategies, have directed whole at the very low development level of experimentation. These conditions have made to appear some discrepancies between us and the progress from Europe and USA. Nevertheless our experiences have a lot of utilities developing some abilities and a favorable opinion for wind energy. After 1989, the year of romanian revolution, have been established the Romanian Wind Energy Association (ROWEA), member of EWEA, which elaborated a first proposal of strategy for wind energy development in Romania. In present it's working with european assistance for a most official strategy of renewable energy sources in Romania.

The main characteristics of the 4 romanian wind units erected upon Semenic site, which are in different working stages, are given in Table 1.

Fig. 1. shows a picture of Semenic site with its four experimental wind units.

TABLE I
THE MAIN CHARACTERISTICS OF FOUR WIND UNITS FROM "SEMENIC" SITE

Characteristics	Unit 1	Unit 2	Unit 3	Unit 4
Rotor diameter	30m	30m	30m	30m
High of tower	30m	30m	30m	30m
Total weight	128t	92t	62t	58t
- Tower (t)	69	51	35	35
- Equipped nacelle (t)	59	41	27	23
Speed (rot/min.)	adjustable 25-37 / 33-50	- 50	- 50	- 50
Rotor position	downwind	upwind	upwind	upwind
Blades:				
- number	3	3	3	3
- aerodynamic solution	without tip spoiler OPSM-7	without tip spoiler OPSM-7	with tip spoiler TVF1/7	without tip spoiler OPSM-7 / import
- technology	steel, welded structure, aircraft	steel, welded structure, aircraft	steel structure covered with polyester reinforced with fiber glass	improved structure (even foreign blades)
Gearing	unintegrated	unintegrrated	integrated	integrated
Hub	welded construction	welded construction	welded construction	welded construction
Wind turbine's shaft and bearings	unintegrated support on the axle and torsion shaft	as unit 1, with constructive changes	integrated	integrated
Electrical generators	2 asynchronous generators of 55 kW and 250 kW with suprasynchronous cascade in rotor circuits	1 asynchronous generator of 315 kW	1 asynchronous generator of 300 kW	1 asynchronous generator of 300 kW
Brakes	2 brakes: - of service, with drum and hydraulic actuator - of damage, on the turbine's shaft, type disc with hydraulic actuators - centrifugal releasing	2 brakes: - of service, with drum and hydraulic actuator - of damage, on the turbine's shaft, type disc with hydraulic actuators - centrifugal releasing	2 brakes: - of service, with drum and hydraulic actuator - aerodynamic with tip spoiler	2 brakes: - of service, with drum and hydraulic actuator
Blades' control	with control system placed on the rotor, with electromechanical drive	with control system placed on the rotor, with electromechanical drive	with aerodynamic brake	adjustable - through a electromechanical system placed into nacelle
Yaw bearing	with balls on 4 ways - electromechanical drive	likewise the unit1	likewise the unit1	likewise the unit1
Cables	fixed with power and control collectors	likewise the unit1	likewise the unit1	likewise the unit1
Electrical panels	partially in the nacelle, partially in the control house	partially in the nacelle, partially in the control house	partially in nacelle partially on the tower basis	partially in nacelle partially on the tower basis
Control	with computer ECAROM changed with PC	with relay	with microprocessor	with microprocessor
Tower	cylindrical section supported on four legs	cylindrical sections and conical section as basis with site welding	three cylindrical sections of different diameters jointed with flanges	three cylindrical sections of different diameters jointed with flanges
Vertical access	winding stairs -	catching stairs with footbridge every 3m	winding stairs	winding stairs
Crane equipment	winch with single rail into the nacelle - possibility to open the nacelle on its front	winch with single rail into the nacelle - possibility to move the equipment through a trap of nacelle's floor	without	without
Measuring equipment	wind direction and speed transducers in front of nacelle, rotation, vibration and temperature transducers	likewise the unit1	likewise the unit1	likewise the unit1
Foundations	weight type with 4 distinct blocks	weight type with ballast	restrained	restrained
Ground plates	double ground plate belt	plug in foundation	plug in foundation	plug in foundation
Transforming station	in control house transformer of 630 KVA + spare of 630 KVA	in control house two transformer of 630KVA	use the station of unit 1	use the station of unit 2

3 PERFORMANCES, MANUFACTURING TECHNOLOGY AND INSTALLING WORKS

3.1 PERFORMANCES

Three of the units existing on Semenic site have been equipped with adjustable blades, and the last has in preparation blades with tip spoiler with adjustment through boundary layer detaching and aerodynamic brake.

The performances verified through measurements for the fist blades set, and the pre-calculated performances for the second blades set are given in Table II; these are competitively with [3].

TABLE II
BLADES PERFORMANCES

Adjustable blade		Blade with limitation of power	
wind speed [m/s]	electric power [kW]	wind speed [m/s]	electric power [kW]
6	6	5	37
7	40	6	62
8	80	7	91
9	120	8	125
10	176	9	165
11	240	10	209
12	296	11	252
over		12	292
12,1	300	13	327
		14	353
		15	367
		20	176
		25	84

Data have been recalculated for the air density of 1,3 kg/m^3 to be compared with [3]. On the Semenic site the air density is in interval of $1 \div 1,15$ kg/m^3.

3.2 MANUFACTURING TECHNOLOGY

Regarding the manufacturing technology the experience shows very good marks for some subassemblies and a little unfavorable for others.

1) Welded steel constructions (towers, nacelle structures, parts enclosed in foundations) : The company STEEL CONSTRUCTION BOCSA S.A. which is the general supplier of romanian wind units, too, have a very good technological experience in the field and it's certified by european bodies for quality (TUV CERT nr. 041004727/03.02.1995) corresponding to ISO 9002/DIN ISO 9002/EN 29002/STAS-ISO 9002.

2) Gear boxes : have been made in two variants, one classical, and one integrated which contain the wind turbine shaft, too. The gear boxes are made at the European guarantee level by a romanian-german company with center in Romania (RENK-Resita).

3) Wind turbine's blades : have been designed in two technological variants, one in welded steel construction, and other a mixed construction composed of a welded strength structure covered with polyester reinforced with fiber glass. Both solutions proved safety. Nevertheless this technology can not compete with the modern polyester structure offered by the european suppliers.

4) Yaw bearing : consist in a heavy bearing with balls on four ways, made in Romania. It assures competitive performances.

5) Electrical and control systems of wind unit : generated a lot of faults during wind units operation. These consist generally in serial components made in Romania that does not assure competitive qualities in alpine climatic conditions. The foreign components offered by the european suppliers will improve substantial the quality of these systems.

3.3 INSTALLING WORKS

Into the frame of installing woks have been tested three foundation systems. We have found that the foundation restrained in the rock layer is the most proper for the site because it makes very small ecological damages.

The erection works had more difficulties because two reasons, the absence in Romania of some adequately roadcrane at rational prices, and because for the erection works have been involved an other company than that which have made the wind units.

4. ECONOMICAL CONSIDERATIONS

The economic analysis developed in parallels with the technical aspects have had in view some directions :
- to improve the aeroenergetic performances
- to reduce some manufacturing and erection works costs
- to improve the quality of components
- to vary some constructive solutions for the tower, gear box, yaw bearing, control systems, etc.
- to reduce the risks through very severe control testing especially at the blades (static loading, vibrations, overspeed testing).

The experience that we accumulated since now, limited yet because the small number of achieved units, permitted to improve the designing having effects in reducing the total weight of wind unit.
We mention that as precaution was considered maximum wind speed at a probability of 1 case at 100 years, determining an extremely control speed of 80 m/s. For the blades was considered a peripheric control speed, for calculation, of 150 m/s and an experimental testing for each blade into an overspeed testing station at 120m/s. The peripheric operation speed is about $55 \div 78$ m/s.

Company "STEEL CONSTRUCTION BOCSA S.A." in present can offer wind units at moderate costs, it assuring the transport on the site and the installing works.

The manufacturing price offered by the company is about 530 $/kW, 24.5% representing the cost of tower and nacelle steel construction, 18,7% blades in steel variant, 43,7% integrated machines line, and 13,1% electrics. The transport and installing works on the site does not exceed 100 $/kW. These costs does not enclose the costs of foundation and transforming station.

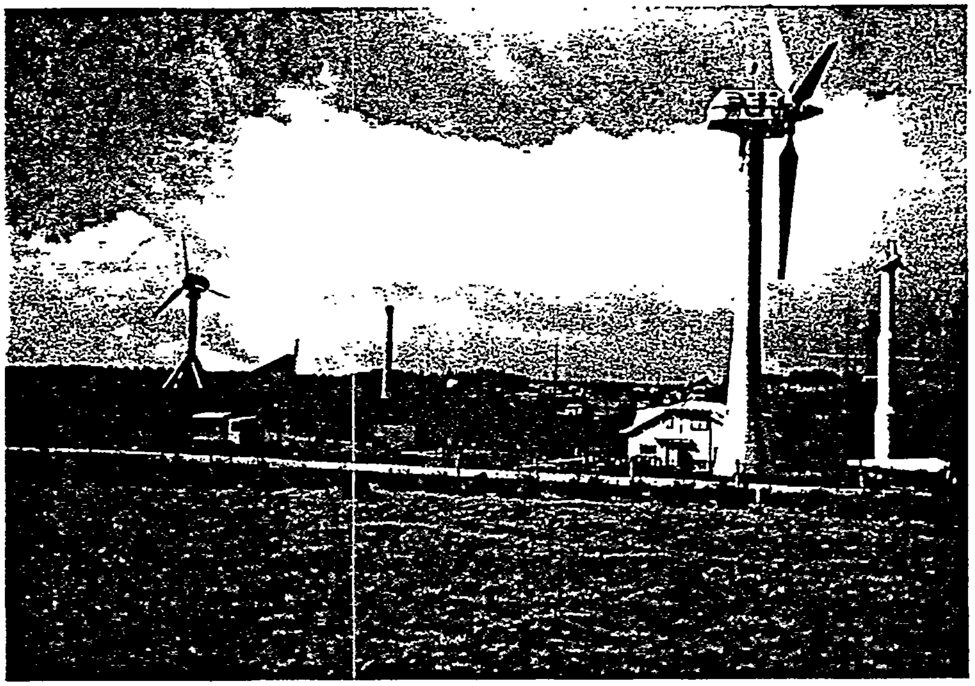

Fig. 1. Semenic site with 4 research wind units, 300 kW each, in different working stages

5. CONCLUSIONS

The potential offered by the Semenic site can represent in the future an attraction for investors. The site through its climatic characteristics and an easy access is a good testing field for the wind units, destined to mountain zones, offered by wind units suppliers.

The local suppliers offer guarantee at european level at moderate prices for towers and other welded steel constructions, at the same for integrated gear boxes. Through these, Romania will be able to cooperate with european companies to achieve some wind units destined to mountain site

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ABSTRACT

Wind power in India which was a meagre 39 MW in March 1990, gradually increased to 122 MW in March 1994 and will be over 250 MW by March 1995. This is compared to the overall wind potential of over 20000 MW and Government of India's target addition of over 600 MW in the Eighth Five Year Plan of 1992-1997. Large capacity additions have been planned from April 1995 onwards mostly in the private sector. This has been made possible by the dedicated and sustained efforts of Ministry of Non-conventional Energy Sources (MNES) and Indian Institute of Tropical Meteorology (IITM) who have laid the foundation in creating the necessary data bank in terms of wind mapping, setting up wind monitoring stations and publishing comprehensive wind data of various locations in India. Formation of Indian Renewable Energy Development Agency Ltd. (IREDA) a dedicated funding agency to support wind energy through attractive schemes; well structured and encouraging polices of Government of India and State Governments in terms of 100 % depreciation as Income Tax benefits, minimal or no duties/taxes, investment subsidies, tax holiday; attractive facilities of wheeling and banking, buy-back and third party selling provided by State Electricity Boards (SEBs) and factors like availability of large area of dry land, minimal running cost and lowest gestation period have contributed significantly towards the growth of this sector in India.

Perpending the above conducive environment, an insight to financial viability presents the key attributes of simple pre-tax pay back period of 5 years and an Internal Rate of Return (IRR) of 25%. The Project cost for an installed capacity of 1 MW hovers between Rs. 40 Million and Rs.45 Million. The capital cost varies as Rs. 18 to Rs.21 per kWhr depending on the location of the project. The factors which affects the economics are selection of site and its cost, availability of quality grid of adequate capacity, type of Wind Electric Generator, terms of finance and micrositing of the machines.

Sensing the large scale potential of wind power, many international manufacturers from Europe and USA have set up their base supplying 200 to 600 kW machines with different configurations, thus offering users enough choice. More and more private sector companies under the captive consumption category are adding capacities in the range of 5 to 25 MW. Added to this is the advent of large scale wind estate developers. Thus, investment in the wind farm sector has come to stay in India.

However, factors like emergence of institutions to undertake large scale wind mapping/wind resource survey to develop new potential sites, indigenisation of various components of WEGs, creation of testing facilities for the performance monitoring of the machines to suit Indian wind conditions and development of suitable and quality infrastructural facilities to match the needs of the industry would make the economics far more attractive, user friendly and help the project to stand individually even in adverse environment.

Kiel, den 20. März 1995

1000 WECs in 6 Years - Wind energy development in Schlewig-Holstein

The State government of Schleswig-Holstein, Germany's northernmost state, located between the Baltic and North Sea, initiated a most ambitious wind energy programme in 1989. A target of 1200 MW, i.e. 2000 turbines, was set for the year 2010.

Only 3 MW were installed at the outset of this programme representing 0,04 % of the statewide electricity consumption. By granting direct subsidies in relation to the investment, and in combination with the nation-wide „100-MW-programme" adding a bonus to the generated kWh, and being particularly helped by new statutory provisions obliging the utilities to pay a fixed price per kWh, the programme took off most successfully.

443 Mio. kWh were generated in 1994, representing roughly 4 % of electricity demand. About 1000 jobs have been created in the windenergy sector according to the local chamber of commerce. Mainly windfarms of 3 or more converters are in operation mostly run by local people, i.e. farmers or associations thereof. A gradual process of upscaling took place - from 100 to 250 to 500 kW per installed WEC. Because manufacturers for the first time had reliable market conditions prices which in the first initial boom went up for a short while have meanwhile came down considerable.

Subsidies therefore could be cut - from an average of 30 % to about 5 %, from 0,08 DM to 0,06 DM per kWh. A target of less than 2.000 DM per installed kW is realistic. The programmes were heavily oversubscribed from the very start. If all projects that are under consideration today would be implemented, the installed capacity would be as much as 1.850 MW. The target of covering about 25 % of the state's electricity demand by wind power by the year of 2010 is very likely to be met even earlier than expected.

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Financial assistance for investments in wind power in Germany - Business incentives provided by the Deutsche Ausgleichsbank (DtA)

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Financial assistence for investments in wind power in Germany - Business incentives provided by the Deutsche Ausgleichsbank (DtA)

1. Introductory note

The reduction of CO 2 - emission and - in view of the limited conventional energy sources - the increased utilization of renewable energy sources are among the essential goals of today's global environmental policy. Within this scenario the use of wind energy plays an important role. However, the cost of generating electricity by wind power can usually not compete with conventional sources, notably because the external costs of generating electricity on a fossil basis are not reflected in current energy prices.

Since the late 80's the Federal Goverment and the State Governments have created a generous financial framework to encourage investments in wind power. This has been done by offering various incentives, particularly by granting direct subsidies and launching new statutory provisions obliging the energy suppliers to pay a fixed price per kWh generated by wind power plants. The DtA as the environmental assistance credit institute of the Federal Republic of Germany has contributed to these efforts by providing loans at preferential interest rates or loan guarantees.

2. Function of the DtA and its key operational areas

The DtA is a federal institution under public law with a head office in Bonn and a branch office in Berlin. The majority of the bank's shares is owned by the European Recovery Programme - Fund (ERP). The bank is active in the field of economic development on behalf of the government. The key areas of economic assistance include:

- Measures to assist small and medium-sized enterprises in Germany and other countries

- The promotion of investments in environmental protection and

- Collaboration in the area of social financing.

Due to the German reunification, the main focus of economic assistance has shifted to the new Federal States.

Since 1972, the financing operations in the field of environmental protection have developed rapidly. Within the bank's environmental protection credit programmes, especially wind energy projects and investments in other renewable energy sources have been supported in recent years.

3. Scale of support

In the business year 1994 the DtA granted loans totalling DM 6 billion to about 5,500 projects in the areas of waste water purification and treatment, waste management, air quality control and energy saving. To support about 500 wind energy projects, ERP loans totalling DM 440 million have been committed in 1994; furthermore we provided additional DtA loans for these projects totalling DM172 million encouraging an amount of DM 914 million of total investment. Regarding the period of time from 1990 till July 1995 we supported 1,585 wind energy projects by granting ERP loans totalling DM 1,037 billion in conjunction with complementary DtA loans totalling DM 429 million, thus stimulating a volume of DM 2, 257 billion of total investment. About 80 % of all existing wind power plants in Germany have been financed through the DtA´s environmental protection loans.

Usually each wind energy project consists of more than one single wind power plant. At present about 2,620 wind power plants with a total capacity of 650 Megawatt operate in Germany, generating environmental friendly electricity of about 1,000 Gigawatthours (Gwh).

4. The DtA`s main support programmes

ERP Environmental Protection and Energy Saving Programme

The main source of financing wind energy investments is the so-called ERP Environmental Protection and Energy Saving Programme. Out of this special programme we grant subsidized, long - term loans. The former four ERP programmes for energy saving, reduction of air pollution, waste management and wastewater treatment were consolidated in this single ERP programm at the beginning of 1995 to facilitate the procedure of application.

DtA Environmental Programme

This additional source of financing offers further low - interest loans for wind energy investments. They complement either the financing available from the above-mentioned ERP Environmental Protection and Energy Saving Programme, or they can also be granted irrespective of ERP financing. These low - interest loans are not subsidized by the government but rather financed by our own return on capital to foster environmental investments. Apart from that the DtA utilizes its excellent AAA bank rating (Moody´s) on the domestic and international capital market to the investor´s benefit.

5. Particular advantages of these loans

Compared to conventional credits ERP and DtA environmental protection loans have several advantages:

- favourable interest rates

On average, interest rates are 1-2 % points below those of the capital market. The current rate of interest on ERP loans is 6,75 % p.a. in the old Federal States and 6,25 % in the new Federal States (disbursement: 100 %). The current rate of interest on DtA environmental loans is 5,75 % (disbursement 96 %).

- fixed interest rates
Interest rates are constant for the entire duration of the loan which may be up to 20 years. Loans may be repaid early at any time and at no additional cost while the DtA bears the risk caused by alterations of interest rates.

- grace period for the repayment of principle
A maximum grace period of 5 years can be agreed on in order to preserve the liquidity of the investor particularly during the initial phase after the investment has been accomplished.

- combination with other financial sources
ERP loans as well as DtA environmental loans may be combined with other disposable grants at the regional, national or EU - level. The DtA itself does not impose any restriction with regard to other financial sources.

6. Prerequisites of support

ERP and DtA environmental loans are available to both domestic and foreign private sector companies whose turnover does not exceed DM 500 million . The projects being supported have generally to be carried out in the Federal Republic of Germany. Companies with a turnover in excess of DM 500 million may be supported if their investment is of particular environmental importance (for details see No. 7). Wind energy projects in general do meet this special demand. Apart from those companies generating electricity by wind power for their own production processes we support those which predominantly transfer their generated electricity by wind power to energy supply units. Agricultural companies which predominantly use their generated energy for own purposes are not eligible.

7. Conditions and restrictions

ERP loans can cover up to 50 % of the eligible investment with a maximum credit amount of DM 2 million (DM1 million in the old Federal States) for each single project. Large - scale projects having an exceptional impact on the environment like those generating electricity by using renewable energy sources can be supported by exceeding the usual limit of credit. The installation of wind energy farms frequently requiring hugh investments is generally accepted as a project of particular environmental importance. The DtA can therefore grant an unlimited ERP loan of up to 50 % of the eligible investment, provided that some addtitional information about the project is submitted:

- typ of plant to be installed
- number of plants
- total capacity
- details about noise emissions
- information about the approval procedure

Furthermore DtA environmental loans up to a limit of 10 million DM for each project can be provided. In combination of ERP and DtA low interest loans up to 75 % of the eligible investment costs can be granted. The location of the project (coastal line, off-shore or interior) does not have any influence on the scale of support.

Financial assistance for environmental investments by loans out of the ERP-Fund are basically restricted to projects carried out in the Federal Republic of Germany. On the contrary the DtA offers low-interest loans from their DtA Environmental Programme also to support transboundary investments in environmental protection as long as they have a significant impact on improving the environment in Germany (cross-border effects). However, the following conditions are to be met:

- The loan/ financing is to be covered by a German credit institute (i.e. assumption of full liability for the repayment of the loan)

- A German company must have a share in the investing enterprise applying for support (minor interest is sufficient), or instead, the loan is to be granted to a German company investing abroad.

Under these circumstances transboundary wind energy projects may be supported out of the DtA Environmental Programme at favourable conditions.

8. Procedure of application

Loans are generally granted in accordance with the so-called "house-bank principle", i.e. through local credit institutions as onlending banks for their borrowers. This procedure emphasizes the basic competitive neutrality of the DtA`s promotional activities and ensures that the knowledge and expertise of local banks are integrated in the procedures of granting loans. Applications from investors are to be made at local banks which then assess the feasibility of the business plan and the viability of the project. The local bank also has to assume full liability.

For investments in the new Federal States whereby loans do not exceed DM 2 million , the DtA may assume 40 % of the risk of the committed loan for the first five years or for the full term of the loan if requested, in order to ease problems relating to inadaequate collateral.

In this context the current discussion in Germany about the legality of certain incentives for promoting wind energy power is of great importance. The enforcement of statutory provisions obliging energy supply units to purchase electricity generated by wind power at a fixed price per kWh (currently 17,28 pfennig according to the so-called "Stromeinspeisegesetz") has been the key factor for investments in renewable energy sources. If these basic revenues are reduced significantly or even abolished this will question the viability of any wind energy project.

A 11

9. Example: Financing of a wind power plant

Project: Installation of a wind farm consisting of 10 wind power plants with a capacity of 500 kw each; the project is of particular environmental importance (unlimited ERP loan)

Investment

fundament	500.000 DM
equipment, machinery	8.500.000 DM
mains connection	700.000 DM
installation costs	300.000 DM
total investment	10.000.000 DM

Financing

own resources	800.000 DM		
ERP Environmental Protection and Energy Saving Programme	5.000.000 DM	**(50 %)**	**} covering**
DtA Environmental Programme	2.500.000 DM		**} 75 %**
Supplementary loans by a local bank	1.200.000 DM		
Additional grants	500.000 DM		
total financing	10.000.000 DM		

10. Additional support programmes

In this respect the so-called DtA Environmental Protection Programme with interest rate incentives from the Federal Ministry of the Environment should also be mentioned.
This programme is designed to support large-scale technical demonstration projects which implement advanced environmental technologies in the areas of waste elimination, recycling and disposal, energy savings, or the exploitation of renewable energy sources.

Since 1991 the DtA has supported such projects by granting loans out of the DtA Environmental Programme covering up to 70 % of the subsidizable investment without a fixed limit. Furthermore the Federal Ministry of the Environment offers a reduction on interest rates of these loans - generally 5 percentage points per year - for up to 5 years of the total repayment period.

So far wind energy projects have not been among those being promoted. But we could certainly imagine to give financial assistance to a new 1 or even 2 MW - generation of wind power plants or to support off - shore wind farms which implement advanced technology.

Apart from that the installation of wind power plants could additionally be supported by providing risk capital out of our Equity Capital Assistance Programme if certain conditions can be met.

11. conclusion and prospect

Within a generous financial framework investments in wind energy power have rapidly increased in Germany since the late 1980´s. In addition to direct subsidies or incentives stipulated by statutory provisions the DtA has encouraged investments in wind energy projects by loans at preferential interest rates with tremendous success and it will continue to do so.

At present we are especially seeking new ways of supporting environmental investments which have a cross-border environmental impact. It is our goal to provide financial assistance both to domestic and foreign companies willing to invest in transboundary projects which may be located in East European Countries. We hope to be able to offer such sources of funding in the nearest future.

Rationality of the Subsidy Regime for Wind Power in Sweden and Denmark.

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Abstract.

This study comprise analysis and discussion of incentives inherent in the Swedish and Danish subsidy regimes for household owned wind power.

New results include an evaluation of the subsidy value of income and VAT tax breaks available to investors, and a demonstration of the importance of the choice of ownership arrangements for the profitability of wind power projects.

The study outlines the complex restrictions associated with different forms of wind power ownership. These cause the investment market to be highly segmented.

The discussion includes several irrational system effects of the subsidy regimes. Among these are collision with energy saving goals, excessive capital costs, dubious siting decisions, and distorted competition among technologies.

In conclusion, some policy recommendations are suggested.

Introduction.

Throughout this century, cheap and plentiful energy was a policy goal for most nations. Only the last twenty years has seen some departures from this goal, particularly in Western Europe and Japan.

Tax breaks and other forms of subsidy were often implemented to support the goal. Tax breaks have mostly targeted the investment process, often through favorable depreciation rules established for specific types of energy production. At the same time, special taxes have been levied on some types of energy consumption, such as fuels for automobiles or electric power for households. The traditional reasons for such taxes have not been energy policy, but fiscal rationality, such as low price elasticity, easy administration, or redistributive justice. In the last two decades, however, energy policy has also become an important reason for such taxes.

This amounts to a somewhat paradoxical situation, where energy is simultaneously taxed and subsidized. In theory, the combination of high consumption taxes with investment subsidies and tax breaks, if carefully planned and implemented, might constitute a powerful set of policy instruments, which in a market setting could transform the energy system in desired directions. But in real life, complex combinations of taxes and tax breaks, decided in different circumstances, by different political coalitions, and for different purposes, may equally well lead the energy system astray, away from economic as well as environmental goals.

This article analyzes and discusses incentives inherent in the Swedish and Danish subsidy regimes for wind power.

Swedish wind power has been taking off in recent years, and now include some 160 mills with an installed capacity of 40 MW. Danish wind power has reached a more mature stage with some 3600 mills totalling 510 MW.

Method.

Starting from interviews and trade literature, prevalent ownership arrangements for wind power were identified. One Danish and three Swedish household ownership arrangements were selected for close scrutiny. A preliminary understanding of each arrangement was developed from the same basis, and from analysis of several investor prospects. Such preliminary understanding, including issues of association law, tax rules, and power law and regulations, was checked, supplemented and refined by confrontation with legal documents and literature.

Rules thus identified were incorporated in a spreadsheet model, accounting for life time project cash flows, contingent on ownership arrangement, national law, and a number of technical and economic parameters, several of which are listed in Appendix 1. Testing of the model included its ability to reproduce calculations from investor prospects and identification of causes for discrepancies.

The model was used to quantify subsidies, particularly differences in tax breaks amongst ownership arrangements and between nations. Results are presented in this article mainly as post subsidy production costs per kWh, as this is the most relevant figure for competition among suppliers to the grid.

The model supports alternative presentation formats, such as the internal rate of return or present value of the project, based on an exogenous power price.

Table 1: Typical 1995 price structures for household power.[2]

mECU/kWh	*Sweden*	*Denmark*
Production and transmission	**26**	**34**
Distribution	10	10
Energy taxes	10	58
VAT	12	25
consumer price	**58**	**127**
excise taxes / pre-tax price	59 %	188 %

Important parameters are listed in the notes[1]. For non-financial costs and technical parameters a compromise was attempted between conservative engineering estimates from Morthorst et al. (1991 & 1994) and optimistic estimates from entrepreneurs and equipment producers. The author has freely defined normatives for returns to investors and parameters for inflation.

Power price structure.

In Denmark as well as Sweden, wind power investments are made chiefly by private households for their own consumption. A commercial price structure for household power is illustrated in *Table 1.* A comparable price structure for household wind power is presented in *Table 2.*

Subsidy rationality.

It is evident from *Table 2*, that subsidies are high in Sweden as well as Denmark. In Denmark they roughly compensate the heavy taxation of household power. In Sweden they amount to a substantial net subsidy.

Do these favors for wind power then drive energy investments in a direction, that makes sense from an environmental and economic perspective? This question may be posed at three different levels:

1. The balance between production and saving of energy.
2. The choice among different technologies for energy production.
3. The details of wind power investment.

The research findings presented in this article relates mainly to item 3. A brief discussion of item 1 and 2 should however establish the proper context.

Balance between production and saving of energy.

On environmental as well as economic grounds, it can be argued that energy savings should be the first priority of energy policy.

The environmental argument would be, that all energy production has negative environmental impacts, and that opportunities for low-impact productions are limited. Low-impact technologies should be used to phase out high-impact technologies, rather than increase total energy production.

The economic argument would be market failures. On the supply side, negative externalities are abundant. On the demand side, transparency and opportunity for rational choice are often lacking, as the consumer is unaware of energy costs or lack insight or incentive to react to these costs. Policies that provide incentives for savings and disincentives for production, could be seen as efforts to compensate such market failures.

If such arguments are accepted, any kind of subsidy or tax break for energy production is suspect. Renewables should be taxed, not subsidized. Coal should obviously be taxed much more.

A household may well face a choice between a wind power investment and an energy savings investment. An incentive for wind power is simultaniously an incentive against using the same money for a savings investment. Furthermore, several of the subsidies for wind power depends on the households own level of consumption. The more power it consumes, the more subsidy is it eligible for.

Table 2: Cost and subsidy scenarios for wind power in the most favored household ownership arrangement[3]. (1995 figures).

mECU/kWh	*Sweden*	*Denmark*
<u>Productions costs</u>		
Initial investment	24	24
Operation, maintenance and renovation	14	14
Non-financial production costs	**38**	**38**
6 % net returns to investor	17	17
Corporate and personal income tax[4]	12	15
Cost of capital	**29**	**32**
Total production costs	**67**	**70**
<u>Value of production subsidies</u>		
Investment subsidy[5]	-15	none
Rebate on distribution costs[6]	none	-3
Refund of energy taxes	-10	-36
Income tax breaks	-12	-15
Value added tax (VAT) breaks[7]	-3	none
Total subsidies	**-40**	**-54**
Post-subsidy production costs	**27**	**15**
<u>Standard distribution and excise charges</u>		
Distribution	10	10
Energy taxes	10	58
VAT[8]	12	25
Consumer price	**59**	**108**

Neither Swedish nor Danish figures in *Table 2* reflect any significant priority for savings. *Table 3* spells this out by comparing the net taxation of wind power consumption with the taxation of energy saving types of consumption (such as buying a warm sweater or a bike) or fairly neutral types of consumption (such as buying a compact disc or having a hair cut).

Table 3: Net taxation of wind power consumption.

mECU/kWh	*Sweden*	*Denmark*
Taxation		
excise charges (energy taxes & VAT)	22	83
subsidies	-40	-54
net taxation	**-18**	**29**
net taxation / un-subsidized production costs		
wind power	-27 %	41 %
standard goods and services (VAT only)	25 %	25 %
net premium for wind power consumption, compared to other consumption	52 %	-16 %

The Swedish figures indicate a significant social preference for increased energy production, rather than savings, if only the technology used is wind power. The production and consumption of wind power gets a 52 % net subsidy, a level otherwise reserved for kindergartens, museums and similar worthy causes. The problem is of course, that low Swedish general energy taxes simply do not leave room for strong incentives to renewables without contradicting priority for savings. The Danish situation is somewhat better, in so much as the general energy taxes are so high, that wind power need not receive a net subsidy. But even in Denmark, a surcharge of 16 % on wind power reflects no strong priority for savings or for energy-lean forms of consumption, and thus no visible acceptance of the above arguments for savings priority.

Against such theoretical grumbling, a pragmatic person might object that higher general energy taxes are no realistic political option. Therefore, subsidy for low-impact technologies must be pursued as a second-best approach. This could be true. But support for renewables might equally well turn out to be a policy that helps keep the energy system locked into the present overproduction/overconsumption paradigm.

Choice among different technologies.

Several technologies for energy production have the potential to reduce the environmental impact of the energy system. In this respect, wind power may well be challenged by other renewables, such as biomass, hydro and solar. Challenge may also come from conversions to natural gas from other fossil fuels, and from more efficient use of coal.

Without careful design, tax breaks and subsidies do not create a level playing field, where these technologies may compete on basis of environmental virtue and economic cost. But careful design is not the rule of politics. Subsidies and tax breaks are often implemented haphazardly, as result of political fascination with a particular technology, as reaction to efficient lobbying, or in support of local or regional development efforts, that are not really related to energy policy. Tax breaks often originate through a combination of entrepreneurial ingenuity and political non-decision.

For a Swedish illustration of this, one may contrast the alternatives of wind power and renovation of small hydro plants. Sweden has numerous small privately owned hydro plants displaying ancient technology, often in a bad state of maintenance. Renovation could often ameliorate the river environment, even with significant increase of power output. But this is perhaps an effort too unglamorous for subsidy. Such small scale hydro renovation gets little of the support available for wind power. Consequently, next to nothing is happening in this field, while wind power in Sweden approaches exponential growth, with a doubling time of less than two years.

In fact, Danish and Swedish wind power programmes have been criticized as examples of undue fascination with a particular technology. Bentzen (1992) reckons that a significantly higher price is paid for avoided CO_2 emission in the Danish wind power programme, than is accepted for alternative means of CO_2 mitigation, such as use of biomass. He deplores the fact, that policy is not based on such rational comparisons. A group at CGM Rationell Planering AB (1993) concludes, that with one exception (public acceptance of new energy technology) the Swedish wind power subsidy does not promote any of the policy goals, for which it is was officially implemented.

The issue here is not, whether this is a fair criticism of wind power policy. It has been challenged by other researchers (Lund 1992; Hedvall, Steen & Stenström 1993). The very debate illustrates however a major problem of technology specific implementation support: It stimulates a process, where the principal competition between technologies is not in the market, but in academic, bureaucratic and political discourse.

Details of wind power investment.

Subsidies and tax breaks for wind power in Sweden and Denmark are much more complex than appears directly from *Table 2*. The favors bestowed on a particular wind power investment depends on the ownership form that is chosen, and on details of the owners personal economy and power consumption. The most common ownership arrangements are described in *Table 4*. The choice again depends on several types of restrictions associated with each arrangement. The restrictions are outlined in *Table 5*.

Actually, only one arrangement is widely used in Denmark. It has been developed bottom-up by local wind power fans, trying to use existing power, tax and association law to their best advantage. Through the years, by effective lobbying, they have achieved changes of power and tax law that further accommodates and enables the typical ownership arrangement. At the same time, restrictions have been made more precise. Thus, a combination of bottom-up initiatives and top-down responses, have carved out one particular favored ownership form.

This ownership arrangement, and the concomitant restrictions, clearly (and intentionally) promotes a specific ownership pattern, which is local, small scale and cooperative. On this basis, a wide distribution of ownership has been achieved. Some 50.000 Danish households, mostly rural or semi-rural, are partners in a wind mill. For the expansion of wind power, this has been an advantageous regime, because it has created a large, organized constituency for wind power politics. It has also worked against some negative images, such as "capitalist speculation", or "outsiders spoiling the landscape". On the other hand, the regime has limited the financial resources available for wind

Table 4: Swedish and Danish ownership arrangements for wind power.

<u>Equity based joint stock:</u> This is the basic form of a joint stock operation, where all capital provided by the owners are in the form of equity. For the purposes of this article, Scandinavian law corresponds to common EU standards of company law. This arrangement is mentioned only as a reference. It is not actually employed for wind power investments in Sweden and Denmark.
<u>Loan based joint stock:</u> This is the same legal form as above, but deployed in a non-standard way to maximize tax benefits. The "shares" in the project consist of a fixed combination of equity and loan, with the equity share small and the loan share large. The loan terms are extraordinary, with contingent amortisation and interest payment. In this way, the cash flow from the project may for several years be distributed not as double-taxed dividends, but as single-taxed interest or as tax-free loan amortisation.
<u>Landowners commune:</u> This is a non-standard legal form. It is a modern elaboration by Swedish legislators on an ancient form of communal ownership (in Swedish: samfällighet), traditionally employed for such objects as grazing or fishing rights. Using this arrangement, a wind mill is seen as a shared assessory for several titles of land, analogous to a shared road or a childrens play ground. The wind mill share is registered to these titles of land. When the land is sold, the wind mill share automatically follows the land, not the owner. The basic rules of the arrangement do not require any specific proximity between the wind mill and the land, nor between the several pieces of land. Mostly however, is it deployed within a local area.
<u>Captive cooperative:</u> The consumers cooperative is well established in many countries, even if there has been little legal standardization. For Swedish wind power investments, it is however deployed in a highly unusual form. A local utility with monopoly on power distribution assists customers with the formation of a wind power cooperative. The cooperative is captive in the sense, that power can only be distributed through the grid of this one local utility, and thereby also in the sense, that owners must stay in the area and consume their share of power through the utility. The arrangement is also unusual because it is in fact a capital based association, contrary to the traditional understanding of cooperatives as associations of either consumers or producers, as opposed to capital investors. Through ingenious legal construction, it is however allowed to enjoy tax benefits, which have been designed for consumer cooperatives.
<u>Partnership:</u> This is the basic common law form of joint ownership. In Denmark, it is the predominant arrangement for household wind power. Partnership production of power consumed in private households by the owners is treated by Danish income tax law as a non-commercial activity, free of income tax. Swedish tax law always requires a partnership to deal with its owners on commercial terms and be taxed accordingly. This makes the arrangement irrelevant for Swedish wind power.

Table 5:
Restrictions associated with different ownership arrangements

legal form	**normal joint stock**	**landowners commune**	**partnership**	**captive cooperative**
country where used	*Sweden*	*Sweden*	*Denmark*	*Sweden*
geographical restrictions				
wind mill location	none	none	none	in an area where the local utility wants to cooperate *(power law)*
owners location	none	none	in the same local government district as wind mill, or neighboring district *(power law)*	in the same utility area *(power & VAT law)*
restrictions on owners type of housing	none	separate house on own land *(income tax & real estate law)*	separate household *(power law)*	separate power meter *(utility requirement)*
restrictions related to owners power consumption	none	*physical terms:* production must not exceed yearly consumption *(income tax & VAT law)*	*monetary terms:* sales revenues must over several years not significantly exceed power expenses *(power & income tax law)*	*physical terms:* production must not exceed yearly consumption *(income tax & VAT law)*
restrictions on trade in shares	none	tied to trade of real estate *(real estate law)*	only to other qualified owners	only to other qualified owners

power projects. Wind power has not been allowed to connect to standard financial markets, nor to great numbers of potential urban investors.

The Swedish picture is more complex. Here, the development of ownership arrangements has also been bottom-up, i.e. a process of utilizing and trying to stretch pre-existing legal possibilities. This activity has not met with much top-down response. No specific ownership arrangement has received top-down blessing and support through accommodating legislation. The Swedish scene is thus more chaotic, but also more flexible. It is chaotic in the sense, that restrictions on different ownership arrangements have not been designed by anybody, but have just happened, as consequence of rationalities quite outside the field of wind power policy. It is chaotic also in the sense, that the individual investor must face a market of bewildering diversity. It is flexible in the sense, that suitable arrangements are available also for the metropolitan denizen, for the investor without long-term stable residence, and for the large scale or even speculative investor. This is a flexibility of choice between arrangements, not a flexibility of the individual arrangement. Each arrangement type has its peculiar complex of limitations, and available tax breaks are tied to distinctive aspects of the arrangement chosen and specific demands on the investors consumption and private economy.

The choice of ownership arrangement has great influence on production costs, as shown in *Table 6.*

Table 6: Post-subsidy productions costs for the same technical project[1], in different Swedish ownership arrangements.

	mECU/kWh
Loan based joint stock:	38
Landowners commune:	30
Captive cooperative:	27

Such differences in productions costs translate into certain effects on the deployment of wind power. The effects are here discussed from two different perspectives:

1. Inefficient siting of wind power.

2. Shortage of financial resources.

<u>**Inefficient siting of wind power.**</u>

To suit technical and socio-economic criteria of efficiency, wind mills should be sited where the wind is strongest, with some compromise to avoid excessive costs for grid connection and transmission, and to avoid nuisance to other land use interests.

Tax breaks however tend to drive wind mills towards other sites. They put a premium upon locations close to investors. A hard incentive is the legal demand for proximity, which is inherent in the Danish partnership and the Swedish captive cooperative. Softer but quite effective incentives are induced by rules that limit the size of individual shares and thus force the combination of a large number of small scale owners. This promotes a community oriented investment pattern, where the wind mill and the investors are located in the same area.

An illustration of siting incentives are provided in *Table 7*. This table compares some investment alternatives available to a household in the city of Lund, Sweden. The comparison is based on real life investment proposals, which were recalculated to allow this direct comparison.[9] Not all incentive for good siting has been eliminated, but it certainly has been much reduced. From the viewpoint of a small investor, there is no economic temptation to choose anything but a local project, regardless of wind.

Table 7: Alternative wind mill locations and ownership arrangements for investor with residence in Lund, Sweden

production per year	example of location	production costs, post subsidy, mECU/kWh		
		joint stock company	landowners commune	captive cooperative
1.080 MWh	Baltic islands	**33**	27	not legal
1.026 MWh	good coastal location	36	**28**	not legal
879 MWh	entry to Lund	43	35	**<u>31</u>**

Casual observation suggest, that bold faced combinations are most popular with investors. Most popular is the one underlined underlined.

<u>Shortage of financial resources.</u>

Contemporary financial markets are deep. In recent years they were able to finance large privatizations and huge government debt. They could provide any amount of capital wanted for wind power, if such investments were perceived as profitable. The mid-1980ies California wind power bubble gave a taste of this.

Scandinavia has avoided repetition of Californian experience, by having doors shut close between wind power and standard financial markets, as consequence of the restrictions outlined i *Table 5*. Other sources of finance were relied on. Utilities were coerced to build some wind mills, particularly in Denmark. A more important source was household finance. Capital was raised directly from households, each typically contributing a minimum of some 400-500 ECU, and seldom exceeding a soft maximum of some 5000 ECU.

Deployment of wind power thus was made dependent on a non-standard financial market with inherent limitations. The ability of households to provide this kind of finance is limited by several circumstances. Household wealth is mostly bound in home ownership and pension schemes. Wealth and particularly free financial resources are unevenly distributed, and many eligible households lack the means to invest, while others have large capacity for investment, but are only eligible for a token share of wind power.

Wind power investments may not have the liquidity wanted by households, nor the time and risk profile preferred. It is not easy for households to evaluate wind power projects, and such involvements may even be felt to transgress economic prudence.

These inherent limitations of household finance are further exacerbated by wind power rules. To get maximum subsidies (Sweden) or even to be allowed to invest (Denmark), households have to be located where acceptable wind sites are available. They should have no intention of moving any great distance. They must be aware the their children are only allowed to inherit the shares if they live in the same area. They must be certain that they will maintain for many years the ability to consume the power, they are signing up for. If any of these conditions are broken they must be prepared for the hardship of selling shares of uncertain value in an illiquid market.

Such limitations can easily cause a shortage of capital for wind power projects. In some regions of Denmark, entrepreneurs report severe difficulties in raising capital, even in the face of positive local response, because a large proportion of eligible households have already invested to the limits. In Sweden there is no such saturation, but entrepreneurs do report paradoxical situations where initially succesful projects are cancelled or greatly delayed because not quite enough local investors sign up, while outside investors have insufficient incentive to join, or may not even be allowed to do so.

In such circumstances, the cost of capital for wind power must be expected to be significantly higher than the general market price of capital. Capital cannot flow freely to wind power projects, as it can to competing technologies and organizations, such as fossil fuel plants commissioned by utilities. If household investors are rational in the economic textbook sense, they must demand a premium on wind power profits to compensate for the lack of liquidity and the concentration of risk, which they must accept as a consequence of market segmentation caused by restrictive wind power rules. They may surely choose to demand no such premium, for idealistic reasons, but then they are really donating their own private subsidy to wind power, on top of what the state provides. Such idealism may certainly shake the conservatism of established power producers, but it can hardly take windpower into the mainstream of contemporary energy investment.

Wind power is thus made more costly by restrictions on ownership. Wind power policies risk getting caught in a vicious circle:

1. The non-financial productions costs are too high to make wind power competitive.

2. Consequently, to promote wind power subsidies are introduced, increased or simply accepted (tax break constructions developed bottom-up).

3. To prevent "misuse" of subsidies, they are tied to ownership restrictions.

4. Ownership restrictions segment the market and increase the cost of capital for wind power.

5. High capital costs further decrease the pre-subsidy competitiveness of wind power.

6. Return to point 2 for a new round ...

Conclusions.

Wind power in Sweden and Denmark is highly subsidized through a broad range of favors, including tax breaks associated with household ownership. At the present Danish level of subsidy, wind power can certainly compete with other energy technologies, if it is allowed access to capital and good quality sites.

In Sweden wind power can compete with existing capacity if investors are willing to bet on good durability of present wind technology.

The article does not argue, that the present level of subsidy is excessive, but does demonstrate several irrational complications regarding the implementation and the interaction with other policy goals.

The implementation regime restricts the flow of capital to wind power projects and should be expected to increase costs of capital, or even foster shortages of capital. The regime reduces options and incentives for good siting.

Being partly tied to a particular technology and to distinct ownership arrangements, the subsidy is not consistent with a desire to create a level playing field for competition among technologies and organization forms to reduce environmental impacts of energy production.

The subsidy is not consistent with a priority for energy savings over energy production.

Policy recommendations.

1. Segmentation of the household market for wind power investments should be radically reduced, in order to decrease capital costs, prevent capital shortages, and establish more effective competition among wind power projects.

2. Ties should be avoided between subsidy and the investors own consumption of power, in order that incentives for energy savings are not compromised.

3. The reasons for maintaining barriers against commercial wind power should be reconsidered, and the costs and benefits of such barriers should be carefully evaluated.

4. Specific wind power subsidies should give way to a regime of more general subsidies, that depend directly on environmental benefits, rather than favor particular technologies.

5. General energy taxes must be substantially increased, to create room for subsidy to low-impact energy production, while maintaining a significant priority for energy savings.

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Notes to text and tables.

1. Wind project parameters employed in the article are listed here. Information in parentheses refers to Morthorst et al. (1994) for comparison.

Base year: *Spring 1995 (Autumn 1993)*

Installed capacity: *450 kW (ibid.).*

Production: *977 MWh/year, when not otherwise stated in tables. This corresponds to an average Danish siting.*

Initial investment, installed and connected to grid: *471 (451) MECU, net VAT.* Operating life: *20 (15) years.*

Operation, insurance and maintenance, stated as yearly percentage of initial investment. In real terms. *Years 1-2: 1,0%. Years 3-5: 2,0%. Years 6-10: 2,4%. Years 11-15: 2,6%. Years 16-20: 3,0%. (Ibid., except for years 16-20).*

Renovation, year 11: *10% (20%) of initial investment, in real terms.*

Termination costs: *none (ibid.)*

General inflation: *3% p.a.*

Post income tax, real terms, internal rate of return to investor: *6% p.a.*

2. Swedish power is typically produced by hydro and nuclear, contributing roughly equal shares. Danish power is based mainly on coal. The figures compared are from two distribution companies close to the Swedish/Danish border: Lunds Energi and NESA.

3. Sweden: Captive cooperative. Denmark: Partnership. See Table 4 for ownership details and Appendix 1 for parameters.

4. A reference level for income tax must be defined, in order to evaluate tax breaks. The reference chosen is a stand alone joint stock arrangement to produce wind power for sale to *non-owners*, financed through a tax-optimal combination of equity and loan. For further description, see Table 4: loan based joint stock arrangement.

5. In Sweden, 35 % of the initial investment is refunded as investment subsidy. In Denmark it could be argued, that some investment subsidy is inherent in the rules for grid connection. The wind power producer pays only for connection to the nearest 10-20 kV line, regardless of the capacity of this line. Beyond that point, all costs for grid improvement is paid by the distribution company (Bekendtgørelse om tilslutning..., 1992). In Sweden it is recommended, that distribution companies charge wind power plants for all investments caused by their integration in the grid (EKOVISAM 89, 1989).

6. Danish distribution companies are obliged by law to pay for wind power at a fixed rate of 85% of their own consumer price, net taxes (Lovbekendtgørelse om udnyttelse..., 1992). The wind power producer thus pays 15% for the service of distribution. This is less than standard distribution costs charged to consumers. The difference is here interpreted as a subsidy to wind power. This ensures comparability between Danish and Swedish figures. It should not be understood as an attempt to estimate the true subsidy value of the grid connection regime, which is a complicated issue.

7. This item reflects the subsidy value of deferred VAT payment. The VAT system is not neutral in regard to ownership arrangements.

8. VAT is the same figures as in Table 1. The power cannot be transmitted as cheap power. The lower price comes out through additional returns from the project, above the normative used in calculation. The connection between this income and a specific consumption is accepted as grounds for exemption from income tax, but not from VAT. The only exception is the captive cooperative arrangement, where a VAT break arises, being treated here as a subsidy.

9. All parameters have been made identical, except tax breaks and power output.

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A Model for Calculating the Economy of Wind Power Plants

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In the Swedish National Board for Industrial and Technical Development's (NUTEK) latest edition of the brochure *Köpa Vindkraftverk* (Buy Wind Power Plants) 1995, a model for calculating the economy of wind power plants is presented.

This brochure is directed towards all wind power interested parties (companies, cooperative undertakings and private persons) who have the intention of buying serial produced wind power plants in the different sizes offered on the market. The brochure is also directed towards building committees and committees of environment- and public health protection in municipalities as well as others who need to consider how wind power plants can come to affect the surroundings.

The brochure describes:

1. How wind power plants can use the wind energy in an effective way
2. The wind as a source of energy
3. Permits required to build and run a wind power plant
4. The construction of the wind power plants
5. The economy of the wind power plants and
6. Forms of ownership

In this paper, I will present the model which has been used in the brochure for calculating economy of wind power plants (that is profitability = incomes - procuction costs); moreover, I will illustrate the model with some exampels of calculations. The model is a result of many years of experience with this type of calculation work carried out by Bengt Simmingsköld, Olof Karlsson and myself.

The costs of the wind power plants are accounted for using both a real and a nominal calculation method. The method has been done in a general way to make it possible to, in a simple way, account for as well investment, operation- and maintenance costs as incomes and production costs (fixed and variable) generated from wind energy production. Moreover, calculations can be done for different sizes of plants, which are built on sites with different wind circumstances and with varying availability of wind power plants.

The real calculation gives a quick overview of the average production cost during the presupposed economic lifetime at a chosen pricelevel. In the nominal calculation (the cashflow analysis), also the cash-flow during the whole lifetime of the plant is demonstrated in a run-ning value of money. In the analysis, the growth of a capital, which is either placed in bonds or invested in a wind power plant, is compared. In the latter case, the net income from the wind power plant is in bonds in a so called "wind bank".

By using the cash-flow analysis, one can also study how the change of a chosen parameter affects the total result and the estimated lifetime of the wind power project. Such an analysis gives valuable information of how a change of different parameters affect the economy of the wind power plants. The estimation may give reason to reconsideration of choise of size, diameter of turbine and of hub hight etc. The model gives the interested party information of appropriate measures, which can improve the economy of the project throughout the whole lifecycle.

The economy of the wind power plants throughout the whole presupposed economic lifetime, can be calculated with use of the following parameters: ***investment cost*** (wind power plant, transformer, power lines, fundaments, montage crane, ground work, road construction, land usage, work planning and permits), ***energy production, receipts from the energy*** (payment from the power utilities, environment bonus and investment subsidies) and ***production costs***, which constitute of both fixed costs (writing off of capital and interest on capital) and variable costs (operation and maintenance cost, insurance, administration etc.).

ARE WIND ENERGY PRICES CONVERGING

by

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ABSTRACT

In the recent Non Fossil Fuel Obligation (NFFO) competition in the U.K., competitors from the UK, USA, Denmark, Japan, Germany and the Netherlands competed by having to bid a price per kilowatt hour for which they were willing to build, finance and operate windfarms. The competition resulted in winning bids of less than 4 pence/kWh with an average (for English and Welsh projects) of 4.32 pence/kWh. It is argued by some that these prices are close to 'converging' with the costs of electricity from conventional power sources delivered to the same point in the distribution system. This paper will give details of the bid prices submitted under the Non Fossil Fuel Obligation and examine the means by which wind energy prices can be made convergent with conventionally generated electricity.

Tariff Based Value of Wind Energy

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ABSTRACT: In this paper an approach for determining a value of wind energy is presented. Calculation is based on wholesale tariffs, i.e. the value of wind energy is defined in comparison with other purchase. This approach can be utilised as an aid in the investment planning in defining the benefits of new wind generation capacity. Linear programming optimization method is used. A case study is presented for different wind scenarios. The value of wind energy can vary remarkably depending on timing of power output.

1 INTRODUCTION

Usually when the value of wind energy is discussed the topics are 'capacity credit', 'fuel savings possibility', 'system reserves' and 'the economic design of wind plants' e.g. [1], [2], [3], [4], [5]. In this paper the value of wind energy is defined assuming that the total installed wind power capacity is low enough not affecting the operation and investment planning of the large power system. In this paper the value of wind energy is defined from a small utility's point of view.

The result of a wind power investment planning is the optimal amount of a new wind capacity. The new capacity can change the optimal wholesale tariff energy purchase. This means changes in the ratios of *base, medium* and *peak* energy purchase. As it will be shown in this paper these changes affect to the value of wind energy and this will, correspondingly, affect to the result of investment planning. In this paper we study the subproblem of optimal tariff purchase in the iterative planning process.

In this paper some wind energy availability scenarios are presented. In a general case they can be replaced by historical data. The scenarios are assumed to be deterministic. Optimal purchase ratios are calculated using Linear Programming optimization method. The values of wind energy in different scenarios are achieved by comparing purchase costs with and without wind energy.

A case study is presented. Optimal ratios of base, medium and peak purchase are calculated. An example load curve, two basic and sixteen artificial wind scenarios are used. In the different scenarios the total wind energy is equal. This approach renders possible to evaluate the value of wind energy in different scenarios.

2 UTILITY'S WHOLESALE TARIFF BASED ELECTRICITY PURCHASE

For utility's point of view a wholesale electric energy tariff is a part of a contract, which defines the utility's possibility to purchase energy from a producer. The time span of the contracts can be from one year up to ten years. Different types of options, which allow utility to adjust their tariff to changing demand, can be included in the contract.[6]

An overlook to the wholesale tariff will be presented as follows [7], [8]. The wholesale tariff defines the energy price between a producer and a utility at every hour of the year. The wholesale tariff contains many different kind of prices. These prices are e.g fixed price, power prices and energy prices. The fixed price is based on customer-focused costs. The power prices to the base, medium and peak tariffs are related to power station investment costs. The base tariff energy prices are primary based on variable production costs of the base power. The medium tariff energy prices are calculated from long term average variable marginal production costs of each different time of a year. The peak tariff energy prices are related to the highest peak power marginal production costs. High energy prices to exceeding energy are introduced. A typical wholesale tariff is introduced in Table I (page 2).

In the wholesale tariff there are also different prices for purchased reactive power and energy. Also a fixed price for additional energy feeding point can be introduced.

A utility can determine ratios of purchased base, medium and peak tariffs. An interesting property of wholesale tariff system is that there exists one optimum for given assumptions that minimizes purchase energy costs.

3 PROBLEM FORMULATION

Utility's electric energy purchase must be in balance with power demand at every hour of the year. In (1) P_t^B denotes purchased *hourly* average base power and P_t^M, P_t^P and P_t^E denote purchased hourly average medium, peak and exceeding power, respectively. The total hourly average power purchased at each hour t, D_t, should be

$$D_t = P_t^B + P_t^M + P_t^P + P_t^E \quad . \qquad (1)$$

At every hour the average base, medium and peak power should not exceed ordered base power P^B, medium power P^M and peak power P^P. The variable P_t^E is positive, if the total power demand exceeds the ordered maximum power.

$$\begin{aligned} 0 \le P_t^B \le P^B \\ 0 \le P_t^M \le P^M \\ 0 \le P_t^P \le P^P \\ 0 \le P_t^E \end{aligned} \qquad (2)$$

Usually the wholesale seller penalizes this excess if it occurs e.g in winter daytime.

Wind energy generated at each hour, P_t^W, reduces the amount of total average power demand in that hour. In (3) P_t^{tot} denotes the total average power consumption and power losses i.e purchased energy at hour t. P_t^W denotes wind power generated at hour t.

$$_t = P_t^{tot} - P_t^W \qquad (3)$$

The total cost caused by other purchase than wind energy is presented in (4) when the constraints, which are (1), (2) and (3), are satisfied. The notation in (4) is as follows

- c_f fixed price, Fmk
- c_o^B ordered base tariff power price, Fmk/MW
- c_o^M ordered medium tariff power price, Fmk/MW
- c_o^P ordered peak tariff power price, Fmk/MW
- c_i^B base tariff energy price, Fmk/MWh
- c_i^M medium tariff energy price, Fmk/MWh
- c_i^P peak tariff energy price, Fmk/MWh
- c_i^E exceeding energy price, Fmk/MWh
- I a set of sets i
- i a set of the equal energy price hours
- t hours

The cost function to be minimized is stated as

$$min(c_f + c_o^B P^B + c_o^M P^M + c_o^P P^P + \sum_{(i \in I)} \sum_{(t \in i)} (c_i^B P_t^B + c_i^M P_t^M + c_i^P P_t^P + c_i^E P_t^E)) \quad . (4)$$

The linear optimization problem is programmed and optimized with GAMS- software [9].

4 A CASE STUDY

4.1 ENERGY PRICES AND DEMAND

Utility's electricity consumption and the wholesale tariff must be known, before the value of wind energy can be defined. Duration curves of each different tariff can be based on measured historical data or defined by other methods [10].

The wholesale tariff used in the case study is of the same kind as IVO H/85 - wholesale tariff [11]. The summer prices are valid from 1 April to 31 October. The winter prices are valid from the beginning of November to the end of March. Week-day hours are defined from 07.00 to 22.00. Night time hours are between 22.00 to 07.00. Holidays and weekends belong to the night time hours. The energy prices used are shown in Table I.

TABLE I: WHOLESALE TARIFF PRICES IN THE CASE STUDY[a]

Tariff j	Fixed price, Fmk/ month c_f	Power price, Fmk/ MW c_o^j	Energy price, Fmk/MWh, c_i^j			
			Summer		Winter	
			week-day	night	week-day	night
B		58000	54	46	54	46
M	62000	32000	113	80	122	103
P		17000	113	80	494	103
Exceeding energy c_i^E			122	122	494	122

a. Based on IVO H/85 tariff

In this example the duration curves for each different *set i* are generated from the typical curves of different type of consumer topography based on the study [10]. The electric energy consumed is assumed to be deterministic. In Table II the energy consumption is stated. The entire energy consumption is 24142 MWh/year. Table III illustrates the number of hours in each *set i.*

TABLE II: ENERGY PURCHASE DATA IN THE CASE STUDY

	Summer		Winter	
	week-day	night	week-day	night
Peak power kW	3732	4219	4364	5114
Energy MWh	6991	4911	6501	5739

TABLE III: HOURS IN THE CASE STUDY

	Hours per each price, h	
	Summer	Winter
Week-day	2625	1845
Night	2511	1779

Figure 1 illustrates duration curves in the case study. Because of rather big deal of households' electrical heating with storage and consumers' two time tariff system, the biggest peak power occurs at a winter night. This does not have an effect on the ordered peak power, although exceeding energy must be purchased. The peak power is defined from the highest peak demand at winter week-day.

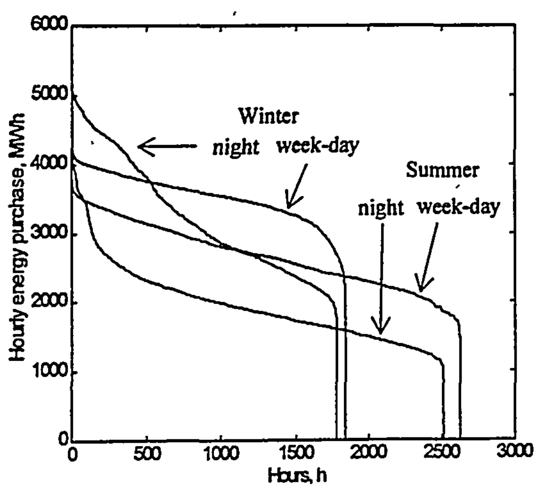

Fig. 1. Duration curves in the case study.

4.2 WIND ENERGY SCENARIOS

Because the price of purchased energy varies diurnally and seasonally, the value of wind energy is highly depending on the time of windy hours and the amount of energy generated. The study of different wind scenarios are needed.

In this paper an artificial cosine wave shaped wind energy profile with one wind energy intensive peak of a year and a day is generated. In (5), (6) and (8) the set *day* is composed of 24 hours. The first member of the set *day* is the first hour of an electrical day i.e. the hour 07-08 am. The set *year* is composed of 365 days. The first day in *year* is 1 January. With parameters *c* and *m* it is possible to adjust the generated wind energy peak to the specific hour of a day and to the specific month of the year. With the scale factor *k* the amount of wind energy can be fixed. P_N is the maximum (nominal) power of wind generator. Some restrictions must be included in the used wind energy profile. The maximum wind energy generated at each hour must not exceed a wind power capacity. The minimum wind power generated is zero. Hourly wind energy, P_t^W, in (3) can be defined from $P^W(h, d)$ in (5).

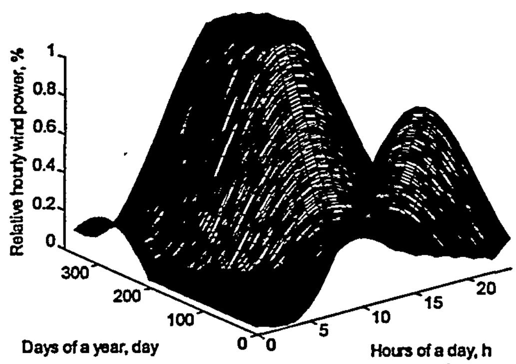

Fig. 2. An artificial cosine wave shaped wind energy scenario.

The wind energy scenarios are stated as

$$P^W(h,d) = max(0, min(1, a \cdot b) - k) \cdot P_N \quad (5)$$

$$a = 0,4\left(-\cos\left(2\pi\left(\frac{c}{24}\right) + 2\pi\left(\frac{h}{24}\right)\right)\right) + 1 \quad (6)$$

$$h \in day \quad (7)$$

$$b = 0,4\left(\cos\left(2\pi\left(\frac{(12-m)}{12}\right) + 2\pi\left(\frac{d}{365}\right)\right)\right) + 1 \quad (8)$$

$$d \in year \quad (9)$$

With k = 0,7 the total amount of wind energy generated is about 33% of the maximum possible generation. This is a reasonable amount of wind energy generated in Finnish wind conditions. This corresponds to the power generation of 2900 hours at the maximum capacity. The wind energy profiles are generated with MATLAB 4.2c- software [12].

In this case study sixteen different wind energy scenarios are examined and compared with two basic scenarios. In the first basic scenario, *Basic 1*, there exists no wind energy production. In the second one, *Basic 2*, the wind energy production is assumed to be constant at every hour.

In this paper a peak of wind energy production occurs once a year. In different scenarios the peak exists in the beginning of January, April, July or November. January and July represent situations, when the most of the wind energy is produced in winter or summer. The wind energy scenarios with the peak occurring at April or November represent the wind energy production, which partly extends over prices valid both summer and winter times.

The peak of wind energy production can also exist at different times of a day. The peak occurring at the time 03.00 or 13.00 represents wind energy production mainly at night or day. The peak existing at the time 07.00 or 22.00 corresponds to wind power production situations, which partly extends over both day and night wholesale energy prices.

In every scenario, where wind energy production is introduced, energy production is assumed to be the same. The average power produced per year is 298 kW with the total capacity of 900 kW. Yearly energy produced is 2609 MWh/year. This is about 11% of total yearly energy demand.

4.3 RESULTS

The aim of this optimization is to study, which are the effects of different wind energy scenarios on purchased energy costs and ordered power P^B, P^M and P^P. For computational reasons the duration curves are reduced and expressed as average values of three succeeding hours. The average energy value without any wind energy *(Basic 1)* is 189,7 Fmk/MWh. Yearly energy purchase costs are 4579558 Fmk. The optimal ratios of tariffs and energy purchase for *Basic 1* and *2* and 16 different wind scenarios are shown in Table IV. The average values of other energy purchase when wind energy is introduced are shown in Table V. In Table VI the average wind energy values are represented.

The values of wind energy are obtained by comparing the yearly purchase costs of different wind scenarios with the *Basic 1*. The value of wind energy is highly depending on the time of wind production. The average values vary from 62,6 Fmk/MWh to 184,0 Fmk/MWh. The highest energy value exists in winter week-days and the lowest in summer nights. The average wind energy value of all studied sixteen wind energy scenarios is 106,1 Fmk/MWh. The constant wind condition (*Basic 2*) results wind energy value of 129,5 Fmk/MWh.

TABLE IV: OPTIMIZATION RESULTS OF THE CASE STUDY

Month	clock	Ordered power kW			Purchased energy MWh			
		B	M	P	B	M	P	E
Basic 1	-	2477	1283	514	19809	2920	1319	94
Basic 2	-	2179	1283	514	17200	2918	1322	94
Jan.	07	2216	1194	766	17459	2263	1784	27
Jan.	13	2250	862	620	18018	1826	1417	273
Jan.	22	2238	1157	706	17959	2085	1488	1
Jan.	03	2254	1222	469	17703	2650	1175	6
Apr.	07	2207	1356	690	17204	2727	1548	54
Apr.	13	2103	1288	632	16883	2887	1597	166
Apr.	22	2233	1308	665	17446	2553	1530	5
Apr.	03	2226	1440	496	17244	3037	1234	19
Jul.	07	2195	1528	548	16534	3472	1434	93
Jul.	13	2071	1607	593	16161	3776	1502	94
Jul.	22	2177	1537	529	16469	3587	1415	62
Jul.	03	2219	1539	516	16548	3553	1367	66
Nov.	07	2231	1302	738	17236	2623	1632	43
Nov.	13	2148	1196	685	17181	2610	1578	165
Nov.	22	2216	1295	699	17345	2584	1601	3
Nov.	03	2268	1340	570	17399	2698	1425	11

In this case study the energy value of energy purchase rises when the wind energy is introduced. That is because of the wind energy is mainly substitute for the base purchase. This results that a proportionally bigger amount of expensive energy must be purchased. For instance, a wind energy production peak existing in summer moves the yearly other energy purchase from the base to medium tariff. That is because of the decreased base energy purchase needed in summer. The peak tariff energy purchase remains almost the same level in every wind scenario. The reason for that is that rather high amount of peak demand hours disperses over long time period i.e. slowly and smoothly decreasing winter week-day duration curve.

TABLE V: VALUE OF OTHER ENERGY PURCHASE IN DIFFERENT WIND SCENARIOS

Clock	Value of energy purchase Fmk/MWh			
	Jan.	Apr.	Jul.	Nov.
07	198,8	201,2	204,3	201,4
13	190,4	196,4	202,8	196,0
22	197,1	200,4	203,9	200,3
03	196,6	201,2	205,1	201,2
Basic 1		189,7		
Basic 2		197,0		

TABLE VI: VALUE OF WIND ENERGY IN DIFFERENT WIND SCENARIOS

Clock	Value of wind energy Fmk/MWh			
	Jan.	Apr.	Jul.	Nov.
07	114,4	94,3	69,2	93,0
13	184,0	134,4	81,7	137,7
22	128,1	100,9	72,6	102,2
03	132,9	95,0	62,6	94,4
Basic 2		129,5		

The variations of energy values can be explained also in other words. The remarkable differences between the wind energy values are due to the fact that the purchased energy values are composed of both energy and power components. The more the generated wind energy is assumed to have capacity credit, the higher is the value of wind energy. For example, the case *Basic 2* in which the wind conditions are assumed to be constant, the wind energy generated is substitute for both base energy and power. In the wind energy scenarios with peak production condition appearing in summer, the wind energy generated is mainly substitute only for energy, not power.

5 CONCLUSION

In this paper the value of wind energy was determined from the utility's point of view. The method is based on the utility's wholesale tariff, the duration curves of each different price sequence and estimated yearly wind energy production. Two basic scenarios and sixteen different scenarios with artificial wind energy profiles are studied. Linear optimization programming method is used in solving the optimal base, medium and peak energy tariffs.

The different values of wind energy arise as a result of the fact that the purchased energy values are composed of both energy and power components. The more the generated wind energy is assumed to have capacity value, the higher is the value of wind energy. For instance, the more wind energy is available in winter, the higher is the value.

In this paper sixteen artificial cosine wave shaped wind energy scenarios were used. At each scenario the peak of wind energy production was placed in different time of a year and a day. Yearly wind energy availability were constant. Because of the cosine wave nature of the wind energy scenarios phenomena of the results became emphasized i.e the highest and the lowest wind values are not likely to appear, if *real* wind data are used.

The method represented in this paper can be applied and put in practice in any real case. Only utility's yearly electric energy demand per hour, the wholesale tariffs and wind energy scenarios are needed. The values of wind energy can be estimated and optimal purchase structure can be calculated.

The use of scenario optimizing methods could be a succeeding step on the road of trying to evaluate the value of wind energy. Different wind scenarios exist with a certain probability and, based on these scenarios, the value of wind energy could be calculated.

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COST BENEFIT ANALYSIS OF WIND ENERGY - A CASE STUDY OF KAYATHAR WIND MILLS IN TAMIL NADU

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COMMUNICATION

Among the various types of renewable energy sources wind energy is stated to be the only proven alternative in the energy structure. Along with the evolution of man from primitive stage to the present civilization the wind energy has also moved with time from its ancient period to the present age of sophistication that is adaptable to various usages like water pumping and power generation. The present paper covers key aspects like wind utilisation in India, wind potentials in one of the windy states viz., Tamil Nadu, in India and economic aspects of the wind energy projects at Kayathar, Tamil Nadu. The conclusions of the paper have few policy implications.

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COST-BENEFIT ANALYSIS OF WIND ENERGY - A CASE STUDY OF KAYATHAR WIND MILLS IN TAMIL NADU

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1. Introduction:

1.1 In recent years we have been encountering what is termed as Energy Crisis. Energy crisis is not only a threat to any economy but also posses a challenge in correcting the deficiency. India which is going in for massive industrialisation is a population giant and has to reckon with the very relevant issue of energy crisis. In this regard the Indian Government has laid a great deal of emphasis on the development and harnessing of alternative sources of energy. Among the various types of renewable energy sources wind energy is present by the only proven alternative in the energy structure. Along with the evolution of man from primitive stage to the present civilisation, the wind energy has also moved with time from its ancient period to the present stage of sophistication which can be adopted to various needs like water pumping and power generation.

1.2 The commercial exploitation of any innovation is to be considered in conjunction with the trios of

1. Potential availability,
2. Practical applicability and
3. Economic viability.

Wind power generation is one type of energy alternative which can satisfy the above.

2. <u>Wind Utilisation in India</u>:

The Indian sub-continent is considered to be a high wind potential zone in Asia which is estimated at about 20,000 MW unlike other renewable energy systems, the wind energy involves the simplest form of technology. Wind energy in Developing Countries prepared in 1988 for the U.S. Department of Energy and the World Bank in which the authors have screened more than 100 developing countries. In applying a comprehensive list of criteria ranging from geographical and meterological aspects from grid capacity and cost competitiveness to technical institution and financial factors they arrive at the ranking where India occupies the second rank having the scope of 79. In our country Gujarat is the most windy state and Tamil Nadu stands next to Gujarat in ~~the~~ creating wind energy. In Gujarat in particular the costal strech between Mandvi and Kaudia of about 100 kms. has an estimated wind potential of 5,000 MW.

Along the Western Coast we have windy sites in Maharashtra, Deograh which have mean annual wind speed of about 19 to 20 KMPH. On the Eastern coast especially in Orissa, Puri wind potential annuall per unit swept area is around 500 kwhr/m^2 yr.

3. Wind Power in Tamil Nadu:

In Tamil Nadu sites like Tuticorin, Coimbatore and Kanyakumari has the wind potential of the order of 520,650,610 kwhr/m^2yr. respectively. Also we have windy sites in Madya Pradesh (Indore), Jammu Kashmir (Baniha, Tojilla), Uttar Pradesh (Kumaon hills) and North Western India (Himalayan range). All the above sites accounts the minimum wind speed required to establish wind farm for power generation. But wind farms are now popular only in Gujarat and in Tamil Nadu.

In Tamil Nadu wind power areas are on the Western side affluenced by Western Ghat. In order to have reliable and useful data of wind potential for two years or more with hourly averages 20 wind monitoring stations have been installed with assistance from the Government of India, Department of Non-Conventional Energy Sources (DNES) is being implemented in Tamil Nadu. Along with the wind monitoring station, Tamil Nadu is having 30 wind mapping stations at different places. Under this programme a cup counter anemometer fined at the top of a 5 metre mast gives the speed of the wind at that height. Readings are taken at synoptic hours viz., at 5.30 hrs, 8.30 hrs, 14.30 hrs, 17.30 hrs and 20.30 hrs daily and the average speed of the wind at the location is arrived.

4. Economic Aspects of Wind Energy:

The following are the main criteria of wind energy regarding economic aspects.

4.1 Wind energy requires high capital cost, but free fuel and relatively smaller percentage of operation and maintenance cost unlike fossil fuel power stations which needs relatively lower capital investment but have recurring fuel cost which estimates around 10 to 15 per cent and relatively higher operations and maintenance cost.

Subsidies and tax rebates offered to wind energy projects from Government of India and the environmental cost to the society.

The most important feature of wind farm is the shorter generation period.

4.2 Benefits from wind electric generates

The benefits from wind electric generators when estimated interms of avoided costs include

1. The savings in capital cost of a diesel generators.

2. Savings in the cost of ~~coal based plant~~ diesel oil used in electricity generations.

3. Savings in capital cost of coal based plant and

4. Savings in fuel costs and operating and maintenance charges.

4.3 The cost-benefit analysis of two wind farms in Kayathar Tamil Nadu had revealed the cost effectiveness of wind energy. The net-present value method is used to find the net social benefit. The net present value is calculated through the following formula:

$$NPV = (Pt\ Qt)\sum_{t=1}^{T} (1+r)^{t} - C_t \sum_{t=1}^{T} (1+r)^{-t} + St + Tx \qquad ......1$$

$t = 1,2,.....T,$

P_t = Price level at time period 't',

Q_t = Total quantity that can be produced at time 't'

C_t = Total capital cost, including operation of maintenance, depreciation, and other expenses at time period 't',

S_t = Subsidies granted by government at time period 't'

T_t = Tax benefit that is available to that project,

$(1+r)^{-t}$ = The discount factor where r = 12% (Bank rate).

On the basis of positive results obtained through net present value method for Kayathar wind farms I and II the economic viability and technical feasibility is ensured (See Table 1).

TABLE 1

ECONOMIC ASPECTS OF WIND FARM IN KAYATHAR

1.	Installation	Plant I 1988	Plant II 1990
2.	Total capacity	2550 kw	6000 kw
3.	Plant load factor	30%	30%
4.	Capacity available/year	765 kw	1800 kw
5.	Price level (Rs.)	1.40	1.65
6.	Expected Revenue	93,81,960	2,60,17,200
7.	Capital costs (Rs.)	510 lakh	1200 lakh
8.	Tax benefit (Rs.)	1,91,25,000	4,50,00,000
9.	Asset value (Rs.)	3825 lakh	900 lakh
10.	Depreciation (Rs.)	17.21 lakh	40.50 lakh
11.	Maintenance (Rs.)	12.75 lakh	30,00,000
12.	Net present value (Rs.)	35.95 lakh	175.6 lakh

Source: Survey Data of the results of the Cost-Benefit Analysis.

5. Conclusion:

5.1 It is necessary to bring down the cost of the raw materials at the international market level and exempt them from sales tax, purchase tax and the excise duty the cost of the raw materials in the market goes up to a great extent with the result the wind turbines manufactured wind equipment could be made available to the consumer at cheaper rates.

5.2 It is also suggested that the wind turbines locally manufactured and the component used for manufacture should be brought under deemed export scheme and such concession would boost the local manufacture to produce wind turbines.

5.3 Involvement for private sector industries in the utilisation of wind energy would be an appropriate step for the development of wind energy in the country. This will not only save the country from power crisis but also conserve the use of conventional energy and save environment from pollution.

It is, therefore, suggested that government may kindly take such step that all the major industrial units in the country could be made to use wind energy or other suitable renewable energy for captive power generation to an appreciable extend, say 30 per cent to 40 per cent of the total power consumption.

5.4 The collected wind data by the nodal agencies should be given to the licensed manufacturers of wind turbines free of cost to that proper estimation of the cost would be made by them before submitting their offer to the customers.

5.5 Institutional arrangements for delivery system should be made in such a way till such time the usage of renewable energy devices at the rural level are achieved for adoption and use.

Joint venture projects to establish manufacturing facilities for projects of solar, wind may be strengthened and refinance as in the case of other programmes are to be increased and motivated for renewable energy devices.

5.6 Mass awareness programme through Television, Cinema, All India Radio, Posters have to be taken up in view of the present awareness programme being inadequate. Energy education and man power development are to be achieved through Primary School, Secondary School, Junior College and Degree levels so as to innovate and improve the technical skills for the purpose. It is utmost essential to provide a certain percentages of budgetary provision in all the special sectors such as women, welfare, forestry, rural development, etc., for energy component to integrate so as to achieve effective planning and implementation.

5.7 The wind characteristics should be carefully analysed to assess realistic energy output. Besides study of variation in wind speed it is also important to study the variation in wind direction for determining the wind farm lay out arrangement.

To conclude wind energy has been one of the few forms of renewable energy which traditionally has been lost effective and practical during previous eras. The present question is whether the combination of improved knowledge of the wind and wind system combined with the rising cost and economic penalities associated with fossil fuels can again lead to the wide, scale contribution of energy from wind. Recent experiments and assessments lead to the probability that this will occur.

RUNNING-IN AND ECONOMIC RE-ASSESSMENT OF 15% WIND ENERGY PENETRATION IN CAPE VERDE

by

Joao Fonseca[1], Jansenio Delgado[1], Jens Carsten Hansen[2], John Olav Giæver Tande[2] and Per Nørgaard[2]

Abstract

In the Republic of Cape Verde, electric power has until recently been almost entirely supplied from diesel power stations - gasoil and heavy fuel. This situation has changed so that approximately 15% of the electricity consumed at the three major power supply systems of Cape Verde is now coming from the wind. During 1994 a wind farm was erected and connected to each of these three major island grids as part of a project jointly funded by the Capeverdian and the Danish governments.

The basis for obtaining the funding for the project was a feasibility study made in 1989, looking into relevant technical as well as economic aspects. A series of assumptions were made knowing that studying a project with such a relatively high wind energy penetration may be associated with considerable uncertainities. Now, having installed the wind farms, a re-assessment of the feasibility of the investment has been performed, both in order to enable an assessment of the possibilities for further expansion with wind power in Cape Verde, and to make results available for other countries and power systems decision makers.

This paper presents the results of the re-assessment of the feasibility of the wind farms now in operation in the three islands, giving annual average wind energy penetrations of approximately 10, 15 and 20%, respectively. The re-assessment is based on the experience gathered during the running-in and initial period of combined power system operation managed by the central power station operators.

Some of the key project assumptions and initial problems encountered that will be addressed are listed below:

- wind turbine availability and grid availability
- wind turbine performance vs contractual guarantees
- wind conditions vs expected
- fluctuations in wind power superimposed on diesel generating sets
- wind power influence on grid power quality
- operation of combined power systems - prevention of black-outs, spinning reserve, optimization
- community development in terms of consumer loads

The economic and financial analyses of the project will be repeated using actual data and up-to-date methods. A brief comparison with the original feasibility study assumptions will be made, but more importantly a "calibration" of up-to-date feasibility study models to suggest the optimal wind energy penetration for the Cape Verde power systems will be attempted.

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Any significant growth of wind generated electricity in the UK can be attributed to the introduction of Non-fossil Fuel Obligation (NFFO) in England and Wales in 1990 and its extension to Northern Ireland (NI-NFFO) and Scotland (Scottish Renewables Obligation - SRO) in 1994. Under these obligations the generators are paid premium price subsidised, directly or indirectly, by the consumers of electricity. In the latest round of these obligations the generators will be paid the bid price varying between under £0.04/kWh and over £0.05/kWh for a period of 15 years. The avoided cost of generation may be taken as the pool price of £0.025 /kWh in England and Wales and somewhat lower in Scotland. The consumer pays in the region of £0.07 p/kWh to the utilities for the use of energy.

This paper examines the economics of wind generated electricity where a generator can utilise part of the energy, hence saving the purchase price. This will cushion the effect of having to sell the excess of energy at a considerably lower price. The cost/benefit analysis becomes complicated and uncertain due to additional charges (not clearly defined and generally subject to individual negotiation) which may be levied by the utilities such as standing charge, availability charge and the reactive energy charge. A number of scenarios have been examined helped with very limited experience of individual contracts with the utilities prior to the introduction of the NFFO/SRO contracts.

REMOTE POWER SUPPLY BY WIND/DIESEL/BATTERY SYSTEMS - OPERATIONAL EXPERIENCE AND ECONOMY

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Abstract. To continuously supply remote villages and settlements not connected to the public grid with electric power is an ambitious technical task considering ecological and economical points of view. The German company SMA has developed a modular supply system as a solution for this task in the range of 30 kW to 5 MW. Meanwhile more than 20 applications of these "Intelligent Power Systems (IPS)" have proved their technical reliability and economical competitiveness worldwide under different, and also extreme environmental conditions. Actually it is the first commercially available advanced Wind/Diesel/Battery System for remote area electrification.

The modular autonomous electric supply systems realized by SMA basically consist of two or more diesel power sets, battery storage with converter, a rotating phaseshifter, and an optional number of wind turbines. All modules are coupled on the 3-phase AC system grid and run in various parallel configurations depending on the wind speed and the consumer power demand.

The control system operates fully automatical and offers a very user-friendly graphical interface. This advanced system control also contains a remote control and operating data output via modem and telephone line.

SMA and CES have considerable experience with Wind/Diesel/Battery Systems for more than eight years. In 1987, the first plant of this kind worldwide was commissioned on the Irish island of Cape Clear, others followed e.g. in Jordan, Australia, Northern Ireland, South Korea, and P.R. China. In many cases wind energy converters in the power range of 30 to 40 kW were used, but it is also possible to use larger wind turbines (e.g. 250 kW).

In the following the system technology is described in detail, experience of different system sizes in several countries of application is presented, and economical analyses for power supply by IPS are given in comparison to a conventional fully diesel power supply.

1 TECHNICAL INTRODUCTION

The Intelligent Power Systems consist of two or more diesel sets, a battery storage with a line-commutated converter, a rotating phase shifter, and an optional number of wind turbines. All modules are coupled on the 3-phase AC side, i.e. on grid side (isolated grid). When there is sufficient wind energy and low consumer demand the wind energy converters will supply enough electric power to be able to switch off all diesel generators.

Due to the fact that the diesel sets have poor efficiency in the "partial load" range (less than 30%), the nominal power of the diesel set is usually sized for about 2/3 of the peak consumer power.

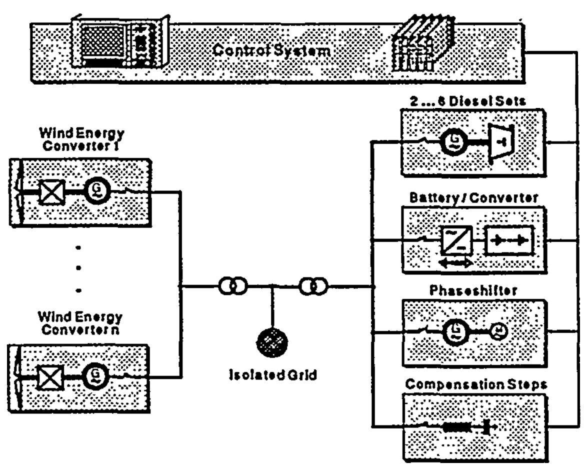


Fig. 1: Principle block diagram of a Wind/Diesel/Battery System

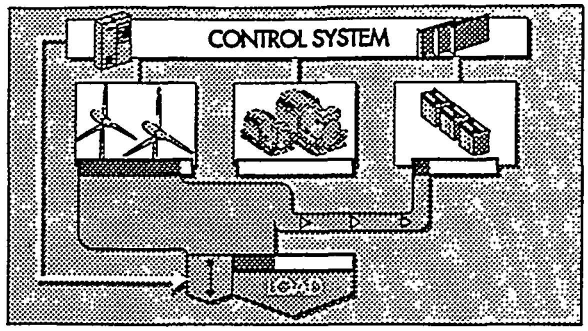
To avoid frequent starting and stopping of the diesel sets due to changing wind velocity or varying consumer demand the system is equipped with battery storage. In this way short-term load peaks in the isolated grid are be balanced by the battery system. It is sufficient to design the battery system as a short-time storage. The supply to the isolated grid or the battery charging is carried out via a line-controlled inverter. This thyristor inverter is a standard product from drive engineering and stands out for its robustness and its good price/performance ratio.

The use of multiple differently sized diesel power sets results in a further increase of fuel saving and economic benefits of the system. The designing of the diesel sets in a two-set configuration should be carried out in a way that the peak consumer power can be supplied by the two engines together, and the smaller one should have half the output power of the greater one. The diesel power sets should be connected in a way that they can be operated as close to their nominal power as possible, i.e. with the highest efficiency.

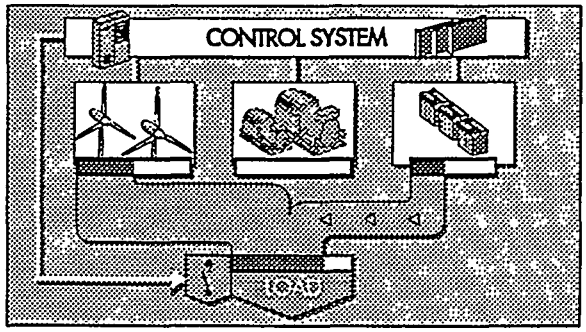
Wind turbines with a good speed/power control via a fast blade pitch setting device are preferably used as wind energy converters. The turbines are equipped with an asynchronous generator, and designed for grid-parallel operation. They can feed the isolated grid at every possible location, because they don't need any additional control lines besides the power connection. Even stall-controlled wind energy converters can be integrated into such a grid.

The microprocessor-equipped operation control selects the most economic and secure operation mode depending on the present power output of the wind energy plant, the charging state of the battery, the load conditions, and the consumer power to be expected.

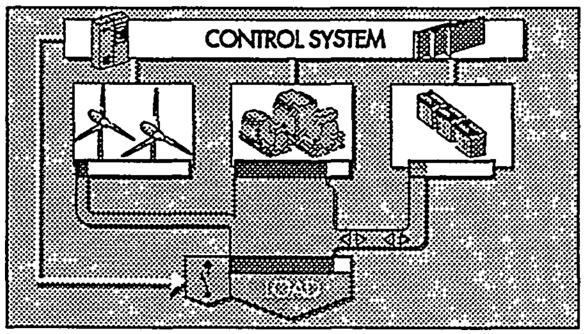
The use of a powerful microprocessor system and a menu-driven graphic operating interface makes the operation simple. The systems contain a remote control and operating data output via modem and telephone line as well as an operating data acquisition and output; furthermore an automatic servicing demand for the several partial systems depending on their operating times.



Special consumers can be switched on by the control system, in cases of a wind energy oversupply.



During periods when the wind energy converter(s) can supply the load, all diesel engines are switched off. Fluctuation of the load or the wind speed is balanced by the battery.



If only a small amount of wind energy is available, one of the diesel sets have to be started.

Fig. 2: Wind/Diesel/Battery System operation during (a) good wind conditions, (b) medium wind conditions, and (c) weak wind conditions

The system conception and the control and supervisory technique are modularly designed not only making possible different system configurations (e.g. diesel/battery systems), but also plants in the power range from 500 kW to 5 MW using bigger wind energy converters (e.g. 250 kW per turbine). Later enlargements or e.g. the installation of PV generators in some years, when photovoltaic will become less expensive, can easily be carried out.

One system configuration in particular shall be mentioned here, which consists of several diesel power sets with different power and a battery storage, but no wind devices. The fuel saving effects resulting from the optimized operation of the diesel engines, the automatic operation, and the remote control via telephone modem make the commercial use of these systems possible in Australia. More than 10 of these plants in the power range from 100 kW to 700 kW are successfully in operation for the supply of remote communities at present.

Generally, in Wind/Diesel/Battery Systems the energy delivered by the wind turbines is about 50 to 70 % and the diesel running time is reduced to less than 40 %.

2 ECONOMIC ASPECT

The economy of Wind/Diesel/Battery Systems mainly depends on two parameters - the wind velocity and the price of diesel fuel. These two factors will determine whether it is more economic to generate electric power from a Wind/Diesel/Battery System or from a simple standard diesel generator. However, Wind/Diesel/Battery Systems have higher capital costs at the beginning which are compensated by lower operation and maintenance costs over the lifetime of the plant. The reduction of operation and maintenance cost (O&M) is gained from

- fuel savings due to energy generated from the wind
- fuel savings due to better loading of the diesel engines (spinning reserve provided by battery/converter system)
- reduced service costs due to less engine running hours
- reduced staff costs due to less emergency 'call outs' (remote failure analysis instead of long distance travelling).

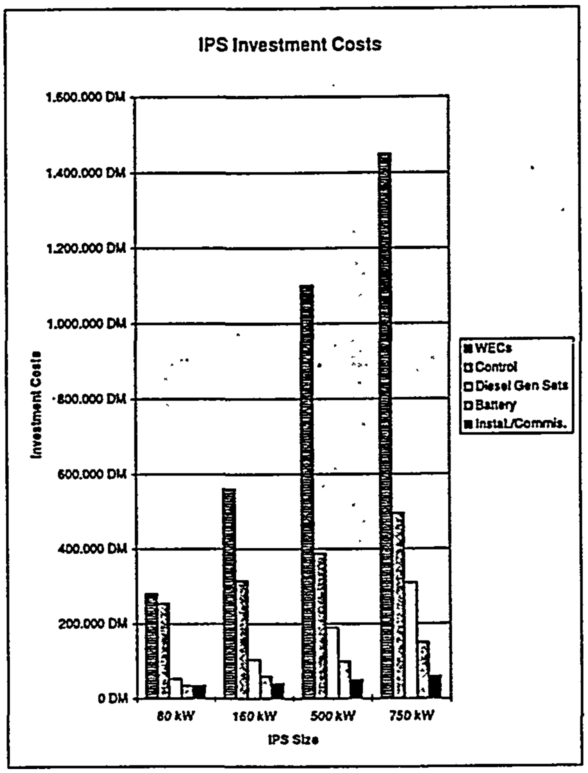
Experience with the remote control network in Australia has demonstrated that the savings made from the remote monitoring and fault diagnostics only, do justify the installation of IPS in the field.

Other financial and technical parameters must also be considered when calculating the economy of Wind/Diesel/Battery Systems. These include possible fuel price increase, interest rate, component lifetime, and servicing costs.

To be able to carry out these complex calculations for configurations and sites, SMA and CES have developed the computer program IPS ECONOMY which calculates the kWh costs for a Wind/Diesel/Battery System versus standard diesel generators using the method of annuity. To use these calculations for the special situation of developing countries and multiple diesel systems, a number of extensions have had to be implemented. The program package is PC compatible and so the costs of the systems can be analyzed with the prospective customer directly on-site.

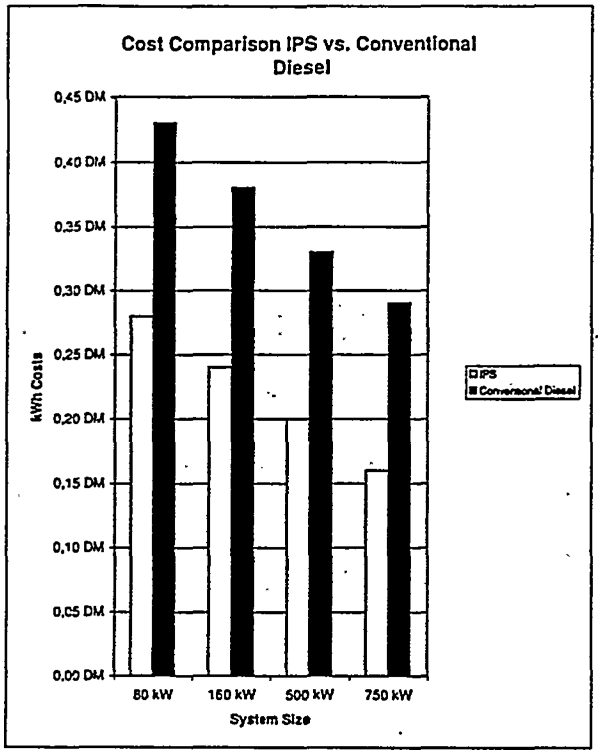
One calculation made by this program for an application in China will be shown in chapter 3.

Fig. 3 shows the costs of the components for IPS systems of different sizes, Fig. 4 the kWh costs in comparison to a conventional full diesel supply for the different sizes. These results show the clear increase of economy by enlarging the system and a reduction of the percentage of the costs for the system technique (control) from 40 % of the total costs for a 80 kW Wind/Diesel/Battery System to 20 % for a large 750 kW unit.



IPS Investment Costs				
Wind Power	80 kW	160 kW	500 kW	750 kW
WECs	280 000 DM	560.000 DM	1.100.000 DM	1.450 000 DM
Control	253.000 DM	315.000 DM	388.000 DM	495.000 DM
Diesel Gen Sets	53.000 DM	105.000 DM	190.000 DM	310.000 DM
Battery	35.000 DM	60.000 DM	100.000 DM	150.000 DM
Instal./Commis.	35.000 DM	40.000 DM	50.000 DM	60 000 DM
Diesel Gen Sets	32,68 kW	68,120,200 kW	100,250,315 kW	120,250,400,600 kW
WECs	2 x 40 kW	4 x 40 kW	2 x 250 kW	je 1 x 250, 500 kW
Battery-system	80 kW	150 kW	300 kW	600 kW
Energy per anno	400 MWh	850 MWh	1645 MWh	3300 MWh

Fig. 3: IPS Investment Costs



Cost Comparison IPS vs. Conventional Diesel (DM / kWh)				
Wind Power	80 kW	160 kW	500 kW	750 kW
IPS	0,28 DM	0,24 DM	0,20 DM	0,16 DM
Conventional Diesel	0.43 DM	0.38 DM	0.33 DM	0.29 DM
Energy per anno	400 MWh	850 MWh	1645 MWh	3300 MWh

Fig. 4: Cost Comparison IPS vs. Conventional Diesel

3 EXPERIENCE AND ECONOMY

In the following two economic calculations for Wind/Diesel/Battery Systems, one in Northern Ireland and the other in China, are presented: The calculation for Northern Ireland is based on data of a full year record of 1994, the calculation for China represents a prediction based on given input data.

3.1 Medium Wind/Diesel/Battery System (Wind Power 99 kW) on Rathlin Island/Northern Ireland

The Northern Ireland Electricity (NIE) as a regional utility operates the autonomous power supply system. The island has a continuously increasing energy demand which is presently at approx. 300 MWh/a. The three wind energy converters of the AEROMAN type have a power output of 33 kW each. Three diesel sets are rated at 48 kW, 80 kW and 132 kW. The battery storage with 110 lead acid cells and a capacity of 73 kWh is operated at 220 V DC. The battery converter has a maximum power of 140 kW. The extraordinary wind conditions on Rathlin Island of around 9 m/s yearly average wind velocity make it possible to shut down all diesel engines for about 70 % of the time.

The system was commissioned in October 1992 and is working up to now very successfully with a reliability of more than 99 %.

The existing system is compared with a conventional diesel power station which would be the alternative power supply. The data for a conventional diesel supply are in accordance with the requirements for diesel power plants.

The energy consumption on Rathlin Island in 1994 has been 307 MWh. Table I shows the frame conditions on Rathlin Island.

Table I
Frame Conditions Rathlin Island in 1994

Average wind velocity:	9.1 m/s
Energy consumption:	307 MWh/a
Interest rate:	8 %
Fuel cost/ltr:	0.5 GBP

1 GBP ≈ 2.3 DM, exchange rate May 1995

The system is designed to allow an increase of energy demand of 20 to 25 % in the next years. This makes the system at present profitable, already for wind velocities of more than 5 m/s average (Fig. 7). - At the moment not all offered wind energy is used.

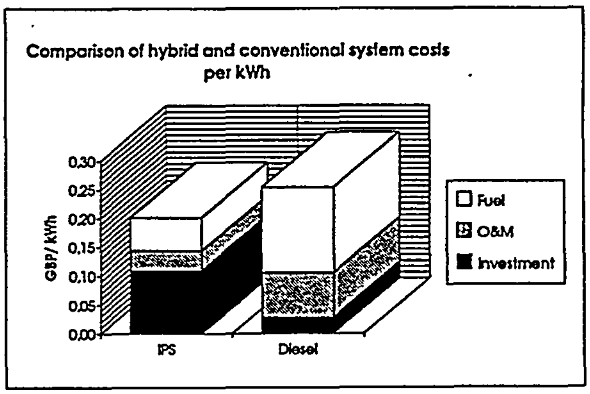


Fig. 5: Specific kWh costs, IPS and conventional diesel system

Fig. 5 shows the energy costs per kWh, divided into investment, operation & maintenance, and fuel costs. This makes evident that instead of the four times higher investment costs a drastic reduction of O&M costs of less than the half and a reduction of fuel costs of more than 60 % has been achieved.

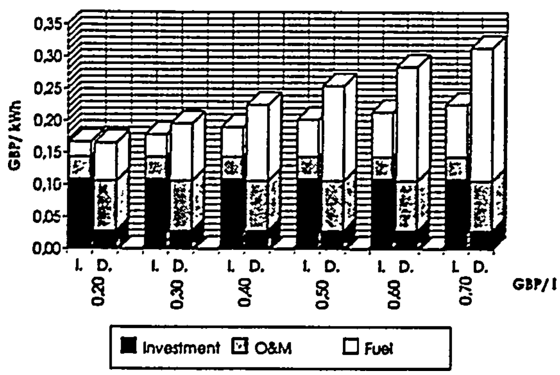


Fig. 6: Variation of fuel costs/ltr, Rathlin Island

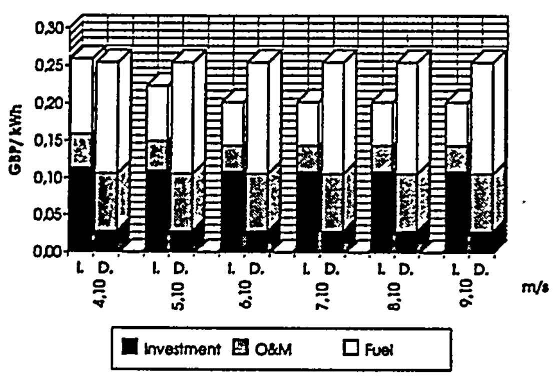


Fig. 7: Variation of wind velocity, Rathlin Island

3.2 Small and Medium Wind/Diesel/Battery Systems (Wind Power 33 and 132 kW) in the People's Republic of China

A small Wind/Diesel/Battery System (wind power 33 kW) located in Inner Mongolia, which is operating since 1991, had to be specially designed for the climatic conditions of Northern China. The temperature range over the year is -40 °C in winter time to +40 °C in summer time with a very low humidity. This system is used as power supply for the Saihantala Wind Test Site as well as a training system for Chinese engineers and technicians. This was the basis for an industrial cooperation between SMA/CES and an enterprise in Inner Mongolia which is supported by the Sino-German cooperation project 'use of wind and solar energy in P.R. China' on behalf of the German and the Chinese Governments. The local content of appr. 40 % for the further systems was the first result of this cooperation.

One of these systems was designed for an island in the south/east of China in the Zhejiang Province. The system which presently is under construction, consists of four wind turbines of type AEROMAN (33 kW power output each), three diesel generator sets rated 75 kW, 200 kW and 200 kW and a battery storage with 100 kWh and a maximum power output of 160 kW. The island has about 5,000 resident population, and besides the household-use, the generated energy is used for the production of fish meal, ice and for workshops. The annual average wind speed has been 7.4 m/s during the last ten years.

The following calculation for the IPS installation of Beiji Island gives the result as a prediction based on given data and compares the full power supply by the wind/diesel/battery system versus supply by conventional diesel generators only. Table II shows the frame conditions for Beiji Island:

Table II
Frame Conditions Beiji Island

Average wind velocity:	7.4 m/s
Energy consumption:	1200 MWh/a
Interest rate:	8 %
Fuel cost/ltr:	3 RMB

1 RMB ≈ 0.2 DM, exchange rate May 1995

For these frame data and a lifetime for WECs and controller of 20 years, diesel gensets of 25,000 hours, and batteries of 8 years, the kWh-costs are given in Fig. 8.

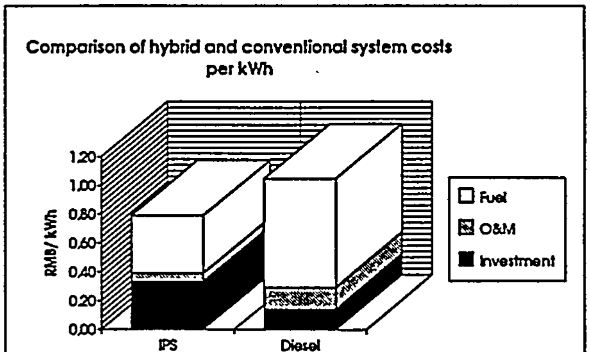


Fig. 8: Specific kWh costs, IPS and conventional diesel system

A calculation of variation for fuel costs and wind velocity is shown in Fig. 9 and Fig. 10. Especially the increase of fuel-costs - which can be expected in the near future - shows the superiority of the IPS. Additionally it has to be taken into account that in many remote areas the reliability of the power supply depends on the transportation of fuel, which is often very difficult and cost-intensive.

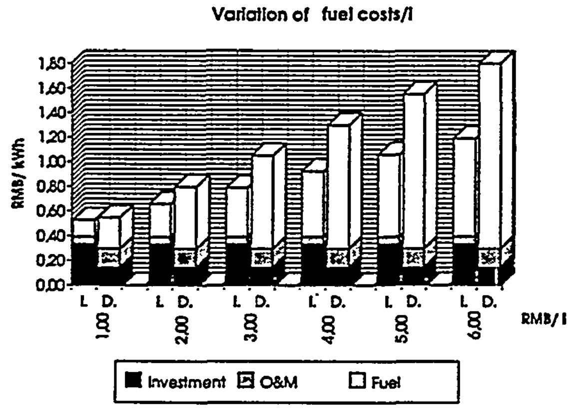


Fig. 9: Variation of fuel costs/ltr, Beiji Island

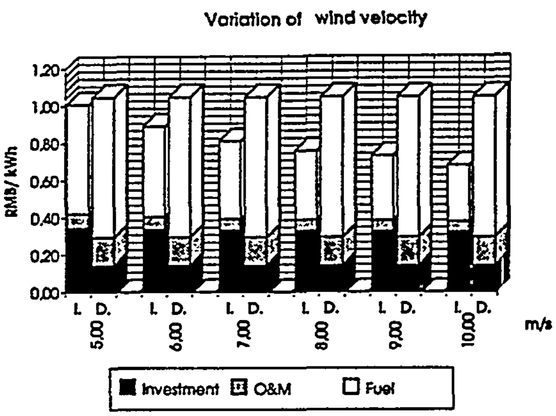


Fig. 10: Variation of wind velocity, Beiji Island

4 PROSPECTS

The IPS systems have proved their technical reliability and economical competitiveness under extreme environmental conditions in very different countries.

Further IPS systems of different sizes and configurations are contracted. Twenty new IPS systems have been ordered by the Power and Water Authority of the Northern Territory in Australia to supply remote communities and expand the IPS network; a large Wind/Diesel/Battery System on the Greek island of Kythnos has been approved by the Commission of the European Union for the Thermie Project. Other projects in South America, India, South Africa, and China are under negotiation.

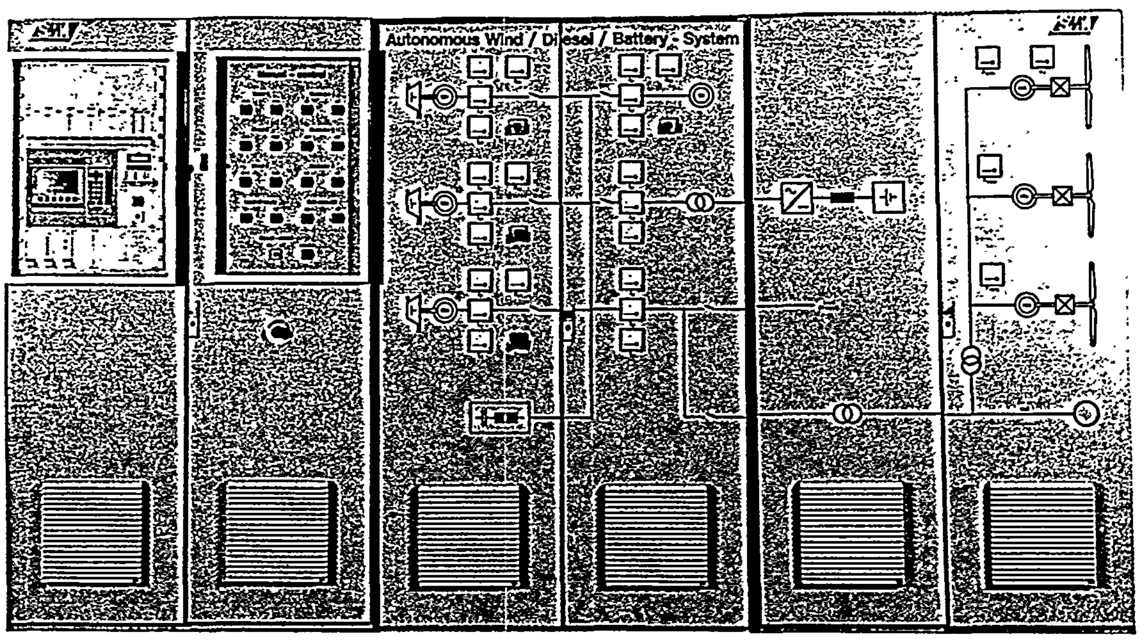


Fig. 11: Switch cabinets of the Intelligent Power Systems

Wind Energy in a Competitive Electricity Supply Environment

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ABSTRACT: In the UK, there has been an increasing interest in the commercial aspects of the impact of wind energy on transmission and distribution networks. In a competitive electricity supply environment, mechanisms for pricing network services are considered to be the main vehicle for evaluating that impact. This paper reviews the major pricing strategies based on embedded costs, short and long run marginal costing theory as well as time-of-use pricing, and comments on the influence of each particular strategy on the calculated value of wind energy. Also, prospective tools for evaluating savings in capital and operating network costs due to wind generation, are identified.

1. INTRODUCTION

Most of the early large embedded generation programmes, and in particular wind energy (WE) programmes, were initiated to provide savings in fuel resources, central generation capacity, and to reduce the impact of conventional electricity generation on the environment. The effect of wind generation on transmission and distribution systems was either completely ignored or treated as a minor issue. However, the situation has now changed and anxieties of high fuel costs and generation capacity shortages have been replaced by concerns and uncertainties in the development of transmission and distribution systems [1].

There have been different schemes in many countries to support renewable energy programmes (eg the Non-Fossil Fuel Obligation scheme in the UK), with the principle purpose to initiate a market for new renewable generation which, in the not too distant future, will enable the more promising renewables to compete without financial support. Although these have led to the unit price of wind generated electricity being significantly reduced over the past few years, it is unlikely that in the near future the price will converge to that of electricity produced at the generator terminals of conventional plants. However, it is now widely recognised that the evaluation of the real value of energy produced by wind generation requires consideration of all the associated costs, not only generator construction and operating costs, but also the savings/increase in both capital and operating costs in transmission and distribution networks. As wind generation is usually located close to electricity customers, it changes demand for transmission and distribution capacity and alters system losses and reliability of supply. This means that, in some circumstances, the electricity produced by wind generators may have a higher value than that supplied by centrally dispatched generation. It is therefore very important to evaluate these effects and explore means of rewarding WE for the benefits it produces to the operation and development of the power system as a whole.

The electricity supply industry, in both developed and developing countries, is entering a period of radical change. The electricity sector is now being vertically disintegrated to allow for competition among generators; centralised generation planning being replaced by market forces. On the other hand, distribution and transmission systems are likely to be forced to operate ever closer to their technical limits, with a great uncertainty of load and generation level and location. It has been recognised that open access to transmission and distribution is one of the essential issues in the deregulated environment, and that pricing of transmission and distribution services is seen to be at the heart of the regulation problem.

It should be emphasised that the impact of WE on operating and capital costs in distribution and transmission systems does not depend on the internal structure of electricity supply industry. However, a competitive environment, by its nature, forces these issues to be raised and discussed, and it is not surprising that in the UK there has been an increasing interest in this area.

It may be argued that neither the present regulated network planning practice nor the commercial arrangements and mechanisms for pricing of distribution services in market oriented structures, treat wind generation (WG) adequately or systematically. The impact of WG on the operation and development of transmission and distribution networks in terms of costs/savings has not been recognised and included into planning programs. Also, in a deregulated environment (as in the UK) the issues related to losses, charges for use of the distribution and transmission system, system running related and reactive power related charges, have been the subject of negotiations between local distribution utilities and WG companies, where many different arguments have been used in different contexts to address essentially very similar questions. Attempts to include the specific features of WG within the present distribution pricing system have not resulted in a consistent commercial framework. As the capacity of WE in Europe is now becoming significant, the impact of WE on the demand for transmission and distribution capacity, on system losses and on reliability of supply, needs to be investigated urgently in order to establish a sound and stable market for WE.

In a competitive environment, the problem of allocating the benefits/costs to WG is an extension of the more general question of pricing for distribution and transmission services. This paper discusses different pricing mechanisms in general, and comments on their suitability for pricing in transmission and distribution systems that include WG.

2. REQUIREMENTS FOR AN OPTIMAL STRATEGY FOR PRICING OF TRANSMISSION AND DISTRIBUTION SERVICES

Pricing of transmission and distribution services affects a power system's operation costs and strongly influences its long term development. It is now being recognised that an optimal pricing strategy for transmission, 'wheeling' and distribution services should meet three principal requirements [2]:

(i) Economic efficiency: tariffs are required to reflect the true economic costs of services provided by sending correct pricing signals to the network users (generators, customers, suppliers), while avoiding any temporal or spatial cross subsidies between users.

(ii) Promotion of optimal network development and revenue reconciliation: tariffs are required to encourage investments that reduce total power system costs and discourage investments that cannot be justified, promoting an optimal development of the network. Tariffs should yield appropriate revenue to the network owners, and enable them to operate and develop the network optimally.

(iii) Transparency and stability: an optimal pricing system should be transparent to all users and provide reasonable stability and predictability of prices.

From the WE point of view, an additional requirement can be identified:

(iv) Capability of dealing with the stochastic output of WG.

It is clear that a pricing mechanism that meets all of the above requirements, should identify, track and evaluate the costs of energy throughout the power system and therefore, enable the additional, real value of WG electricity to be quantified. This would then enable a market for WE to be established, and possibly make WE more competitive. To the best of the authors knowledge, however, such a strategy has not been proposed yet.

3. MECHANISMS FOR PRICING OF TRANSMISSION AND DISTRIBUTION SERVICES: A REVIEW

Early interest in the pricing of transmission services, particularly in the US, was mainly to do with the inter-utility wheeling of electricity over the transmission network of an intervening third utility. Several simple methods were applied at that time without use of detailed economic analysis. However, there has been an increasing awareness of the need for pricing for the use of transmission and distribution services with recent moves to de-regulate the electricity supply industry and to provide open access to networks (i.e. the UK case), or third party access to the network for non-utility generators (the US case).

In general, all mechanisms, in use or recently proposed, for pricing of transmission and distribution services may be classified into two major categories: pricing based on marginal costs and pricing based on usage. It should be emphasised that the latter is extensively used in the US, while the former has been recognised as more appropriate in the UK, Chile, Argentina and some other countries.

3.1 METHODS BASED ON USAGE [3]-[8]

There have been a variety of different scenarios based on the network usage approach, particularly in the US, mainly for wheeling purposes. This method basically concentrates on two measurements: the amount of capacity used and the per unit cost of transmission capacity. Measurements of transmission capacity used can be as simple as total megawatts of a wheeling transaction or involve calculation of estimated or actual power flows and related transmission data. Costs of transmission capacity are usually calculated on an embedded cost basis.

The main logic behind the methods based on embedded costs is that every producer or user of electricity uses the network and should pay for that[1]. It is clear that those methods have no appropriate grounding in economic theory, and apart from stability in prices do not satisfy any other requirements for an optimal pricing strategy. This approach will not suit WE as it does not recognise any savings in operating or capital costs which may be caused by usage.

It is, therefore, now being strongly argued, that embedded cost based evaluation and pricing based on usage does not provide a basis for efficient network operation and development.

3.2 SRMC BASED PRICING [9,10]

The short run marginal cost, at any point in time, of operation of the electric power sector as a whole is the marginal cost of supplying an additional unit of demand holding the capital stock constant. Conventional economic theory favours SRMC based pricing where network costs are represented in terms of marginal costs of losses and 'congestion', recognises the variation of the costs in time and space. Practical implementation of this strategy would require real time metering at all load and generation points, as the prices for the use of system would vary accordingly. As the load and generation are treated equally, negative charges are possible. This pricing mechanism would achieve requirements (i) and (iv) of the desired optimal pricing strategy.

From a WE point of view, this form of pricing would recognise the impact of WE on distribution and transmission system losses and out-of-merit order (security) costs in real-time, but not the impact on capital costs and reliability of supply (long-run impact).

Also, network owners would not be entirely satisfied by this strategy as the network business is dominated by capital investments and the revenue requirements from the network operation would be highly uncertain. Furthermore, it is important to note that SRMC based pricing gives perverse incentives to the network owners, as the revenue increases when the network performance deteriorates. Therefore, in the long run, this pricing mechanism would not be optimal

[1] An exception is the 'zero counterflow method', where a particular user is not charged for the use of system if the use of the network produces a couterflow to the net flow.

(requirements (ii) and (iii) are not met by this approach).

3.3 LRMC BASED PRICING [9,10]

The long run marginal cost (LRMC) of the electricity power sector is defined as the marginal cost of supplying an additional unit of energy when the installed capacity of the system is allowed to increase optimally in response to the marginal increase in demand. As such it incorporates both capital and operational costs. LRMC would provide a tariff today based on the predicted cost of future system operation and investments. Therefore, LRMC based pricing requires long-term assessment of future generation costs, capacities and sites, together with demand profiles and corresponding geographical data. Also, in a deregulated environment centralised generation planning has been replaced by market forces and these will, in the future, enter transmission and distribution businesses although in some somewhat different form. It is considered that, because of the high uncertainty associated with these factors, LRMC prices do not have very much practical value. While the prices would be stable in the short run, they tend to be more volatile on a year by year basis.

As the implementation of the LRMC prices, would require long-term forecasts and predictions of future technical and economic developments, the position of WG in those plans would determine significantly its future development. In the UK, LRMC based pricing is not considered as an appropriate mechanism, as deregulation is planned to be extended further.

It should be noted that at the limit LRMC and SRMC arrive at the same point for an exactly optimally developed system. This has significant theoretical, but not corresponding practical, importance.

3.4 INVESTMENT RELATED NETWORK PRICING [11]

This method is currently in use in the UK for pricing the use of the transmission system. An optimisation model, based on a modified transportation model, was developed to calculate optimal transport of power in MWkm on the system. The method includes Kirchoff's laws and security requirements. Assessments of this approach indicate that some 68% of the asset value of the current transmission system is required for security and 22% for the plain transportation of energy, while the remaining 10% is present due to forecasting errors in the planning stages, indivisibilities and other system requirements such as stability and voltage limits that were not modelled in detail. Corresponding charges significantly vary with location. At present, there is no charge for demand in the north of England, while in the south the annual charge is 22,100 £/MW. Generation in the north pays 8,500 £/MW for the use of system, while in the south it receives 7,900 £/MW for generation at peak times.

It is important to emphasise that this pricing strategy recognises the positive influence of some users on network capital costs (negative charges for generators in the south), and provides some incentives to the network participants to use the network more economically. The benefit that the operation of a wind generator makes in terms of reduction of transmission capacity, could be seen not only by the transmission utility and other users of transmission system, but also by the wind generator which created the benefit. At the moment, however, this benefit stays with the local distribution utility and customers supplied from the corresponding grid supply point (as they pay lower transmission system charges and are therefore being subsidised by WE).

As the charges are based on mean kW over three 1/2 hour periods of peak demand in the year, this mechanism introduces uncertainty to the transmission system charges, which may be very important for WE. This is because it may happen that there was no wind at the system peaks, or that some turbines were out of service at that time, and the positive contributions made over the year would not receive corresponding credits.

Furthermore, charges for the use of transmission system reflect cost for capital investments, but not the cost of the operating the system. Also, the strategy lacks firm economic grounds (requirement (i)).

3.5 TIME-OF-USE BASED PRICING [2]

A substantially new, time-of-use site-dependant approach to pricing of transmission services, where the optimal demand for transmission capacity is determined through a trade off between 'out-of-merit generation costs and transmission system costs, has been recently proposed by Farmer et al [2]. It proposes a medium-term tariffing period (one or a few years) considering operating and annuitised capital costs incurred by the transmission utility over that period. The approach utilises conventional economic analysis by deriving the 'demand for transmission capacity' in relation to the prices assigned to the circuit flows and the economic benefit attributable to the transmission services provided. The benefit is quantified in terms of marginal reduction of generation costs and enhanced security of supply. This strategy may be regarded as a multivariate transmission analogue of the peak-load pricing, previously employed in the time-of-use pricing of electrical power generation [12].

It should be emphasised that this strategy closely conforms to the first three requirements, with firm economic and technical grounds. The charges are based on kWh over several long periods and this generally suits WE.

3.6 FURTHER DEVELOPMENT

This approach, however, requires further development in order to include the impact of the stochastic nature and availability of WG and uncertainty in the network loading on the system capital and operating costs. This is one of the fundamentally important issues for the evaluation of the real value of WG and for the pricing of distribution services particularly in networks with WG. Also, there is a need for more appropriate treatment of all non-dispatchable generation. Furthermore, this concept could be further extended to a cost-benefit based distribution system pricing mechanism in order to include the impact of WG on reliability of supply and corresponding outage costs. Outages and associated costs are now becoming recognised as increasingly important commercial issues. In the developed countries, which are also leading in the development of WE, the contribution of WG to reliability improvement may become very significant.

Therefore, the pricing of distribution services, considered in association with investment, operating and outage costs as well as reserve management, would inherently require a probabilistic, not a deterministic, treatment. This is a new area of research and a fundamentally different methodology needs to be identified and established to support its practical implementation. The authors are currently investigating this approach.

4. METHODOLOGICAL FRAMEWORK FOR THE IMPLEMENTATION OF PRICING STRATEGIES

A common characteristic of all the pricing strategies based on marginal costing theory is that the prices are calculated in an optimisation procedure that minimises some costs, taking into consideration basic laws that govern electricity flows, technical constraints related to security requirements and possibly some economic constraints related to revenue recovery. The prices are then calculated as shadow costs associated with a set of constraints, depending on which strategy is chosen, using standard post optimality analysis.

It should be emphasised that the simplest investment cost related transmission system pricing, developed and used by National Grid Company in the UK, uses some advanced techniques to actually calculate the corresponding charges for the use of transmission system. Time of use pricing, which is likely to replace the current scheme, is even more complex from that point of view. However, the regulator and the industry take view that if some additional complexity of calculation can improve economic efficiency and brings some benefits and savings, than its use is justified.

It is therefore reasonable to expect that the incorporation of specific features of WE will require even more complex mathematical models to be used. As it is mentioned above, the stochastic output of WE require a probabilistic formulation of the problem, where conventional load flow calculations will be replaced by probabilistic load flow calculations, while deterministic optimisation will be replaced by stochastic optimisation.

5. CONCLUSIONS

This paper gives a review of strategies proposed and/or applied for pricing of transmission and distribution services. Particular emphasis is on the impact which different pricing mechanisms would have on the evaluation of the value of wind energy and its further development. Currently available schemes are not satisfactory, and further research in this area is needed. A strategy for pricing of transmission and distribution services, that takes account correctly of the presence of wind generation is likely to be based on stochastic optimisation.

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PERSPECTIVES OF DEVELOPMENT OF THE STAND-ALONE MODE WIND ENERGY SYSTEMS IN RUSSIA

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As much as 75% of territories in Russia do not have any kind of grid electricity supply, and this, of course, influence greatly on the productive activities and social life-level of the population on these territories. Rapidly increased prices for a good deal of energy sources (oil, gas, coal) have lead to a very difficult situation in many regions, especially in the field of guarantying of local needs in electricity and heat with the help of recently traditional sources of energy (mainly diesel electric stations). Perspectives of connecting remote regions to the central grid systems are meaningless, that is why the research and production of the autonomous wind energy systems is essential for Russian research and manufacturing enterprises.

Nowadays a range of energy systems is developed for different groups of consumers and the range offered consists of wind generators, solar-batteries, micro-Hydro Electric Stations and Stirling-engine thermoelectric units of different power-level. Stirling-engines are designed for the work with any kind of liquid, gas or solid fuels.

A group of the Russian firms work in the field of design and production of wind energy stations of different power level (in the range from 50 W to 30 kW) for the purpose of using them in autonomous mode. Design characteristics of the most typical wind energy systems are examined. In detail the design of the wind energy electric station M-250 produced by Molinos Co.Ltd is examined. The prices of the M-250 details is shown.

Absence of the State programme for using of wind energy and the State legislation, which can stimulate the using of renewable sources of energy, is the key factor restraining the development and using of wind energy systems in Russia. The development of renewable sources of energy in Russia fall behind the same process in other countries. Because of this, other countries can participate in the development of Russian renewable energy market. For example, foreign countries may sale the licence for manufacturing energy systems in Russia, take part in joint ventures, put investments in the energy sector. Great interest should be paid to the production of house-hold equipment (lamps, TV- and radio systems, washing [illegible] which can be effectively used with autonomous energy systems in the remote regions.

Costs of the grid connection of wind turbines

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ABSTRACT: The costs of the grid connection of wind turbines in Sweden have until now been about 5 % of the total investments, provided that the distance of the connection cable is limited. Now the grid will soon be filled locally and it will be necessary to strengthen it. The costs for this can also be about 5 %, and the total cost about 10 %. Improvements in the electrical systems of the wind turbines and the connection technique can give less disturbance in the grid and diminish the costs. It is important to agree on how to share the costs for strengthening the grid. Otherwise, it can become an obstacle when building new wind turbines.

1 INTRODUCTION

About 175 medium-size wind turbines have been built in Sweden until now, most of them during the last two years. Depending on the grid stiffness and configuration, the ways and the costs of connecting wind turbines to the grid vary widely from site to site. The easiest way to connect a wind turbine to the grid is via the low-voltage side of existing distribution transformers. Some of the wind turbines in Sweden are connected in this way, especially where the site is close to a densely built-up area. The opportunity will, however, demise with increasing generator power due to limitations caused by the voltage drop. And locally the existing grid already begins to be filled. New power lines must be built, and consequently the costs of the grid connection will increase.

The aim of this work is to make a survey of different ways to connect wind turbines to the grid, the regulations for this and the influence that this will have on the costs of the grid connection.

2 RECOMMENDATIONS FOR GRID CONNECTION

Several recommendations and standards for wind turbines have been developed during the last decade. In Sweden, the electrical connection of wind turbines is regulated by the technical instructions, TAMP [1], and the dimensioning instructions, DAMP [2]. Both are produced by the electric power distributors' association, Svenska Elverksföreningen. Moreover, a new IEC-standard for wind turbines, TC-88 [3], has been accepted. In this paper some headlines in the IEC regulations will be discussed and compared with the Swedish regulations, TAMP and DAMP. Some inputs to these recommendations are coming from the Danish wind turbine experiences [4].

2.1 SUMMARY OF RECOMMENDATIONS

1) General: According to TC-88 wind turbine operation and safety should be governed by a control and protection system. .

2) Protective devices: Besides the ordinary protection devices, equipment should shut down the wind turbine safely, if the conditions of the external electrical systems do not allow continued safe operation.

3) Power collection systems, conductors: All electrical cables, devices and assemblies should be installed, wired and connected in accordance with relevant IEC standards. According to DAMP [2], voltage variations in the cable between the wind turbine and the transformers may not exceed 2.5 %. This should be checked by using the formula:

$$R \times P_v - X (Q_v - Q_c) \leq 4$$

R = resistance of connection cable (Ω)
X = reactance of connection cable (Ω)
P_v = generator-rated power (kW]
Q_v = generator consumption of reactive power (kVAr)
Q_c = power plant compensation of reactive power (kVAr)

In order to keep the voltage variations within these limits, some easily readable graphs concerning the choice of cables are presented in DAMP.

4) Phase-compensating capacitors: If a capacitor bank is connected for power factor correction, a suitable switch is required to disconnect the capacitors. This precaution is due to the risk of self-excitation of the generator in case of grid failure. Swedish regulations, TAMP and DAMP include rules concerning power factor correction and the maximum size of capacitor banks.

According to TAMP, a rule of thumb is to compensate for reactive power up to a third of the apparent power of the generator. This compensation corresponds to a power factor between 0.90 - 0.95. According to DAMP, wind parks ought to be compensated for the power factor 1, by a central capacitor bank. In order to avoid voltage fluctuations, the capacitors should be switched in steps of 30 - 40 kVAr.

5) Harmonics and power conditioning equipments: The power conditioning equipments, such as inverters, power electronic controllers and static VAR compensators, should be designed so that the harmonic current and the voltage wave form distortion are minimized and do not interfere with protective relaying.

In DAMP harmonics are allowed in accordance with the Swedish standard SS 412 18 11, see table 2.

TABLE 1
SELECTION OF TRANSFORMER CONSIDERING GENERATOR POWER ACCORDING TO DAMP

- 30 kW	50 kVA
30 - 70 kW	100 kVA
70 - 150 kW	200 kVA
150 - 200 kW	315 kVA
200 - 300 kW	500 kVA
300 - 400 kW	630 kVA
400 - 600 kW	800 kVA

TABLE 2
VOLTAGE IRREGULARITIES ON LOW VOLTAGE SYSTEMS ACCORDING TO THE SWEDISH STANDARD SS 421 18 11

Voltage	Specification	Reason	Causes
Slow voltage variation	+ 6 % - 10 %	Load variations	
Sudden changes in the rms of the voltage	"Flicker curve"	Switching loads Utility switching	Flicker Computer system crashes
Voltage fluctuation		Motor starting	
Harmonics	Odd ≤ 4 % Even ≤ 1 % THD ≤ 6 % (n = 2 - 40)	Non-linear loads Motor speed controllers Inverters	Additional losses in generators and transformers Inceeasing current in capacitors
Inter harmonics	≤ 3 %	Frequency converters	Unstable operation of sensitive electronic equipment

6) Special regulations in TAMP and DAMP: There are some additional regulations in TAMP and DAMP. The ratio between the short-circuit power and the rated power of the wind turbine must be at least 20. The transformer must be chosen in accordance with table 1 from DAMP.

2.2 POWER QUALITY

Power quality is only discussed shortly in this paper. The question is dealt with more in detail in [6]. Many of the restrictions in the recommendation listed above are based on power quality demand. The rules are often based upon estimations, not measurements. There is an uncertainty about how to measure some of the factors. An EU project, " Power Quality of Wind Turbine Generator Systems and their Interaction with the Grid", within the JOULE-II-programme, deals with how to measure. The final report will be issued at the turn of the year 95 - 96. The most important irregularities and their limitations according to the Swedish standard, SS 421 18 11, are listed in table 2.

FACTORS OF COSTS

The easiest way to connect a wind turbine to the grid is via the low-voltage side of existing distribution transformers. Only cable, digging, wiring and coupling are needed. The opportunity will, however, demise with increasing generator power.

Because of power quality demand and because wind turbines have become larger, the ordinarie size today is 600 kW, it will normally be necessary to install a new transformer especially for the wind power plant and connect it to a higher voltage. Often the transformer also need a transformer station. If the power production is limited up to about 250 kW, a simple pylon-station can be used.

3.1 COSTS OF PARTS

1) Cables: The costs of a low-voltage aluminium cable will be about 10.5 ECU/m (based on prices in Sweden, exchange rate: 1 ECU - 9.50 SEK) for 150 mm² and 16 ECU/m for 240 mm².

Medium voltage aluminium cable amounts to 16 ECU/m for 50 mm² and 23 ECU/m for 150 mm². An overhead power line, 95 mm², costs about 18 kECU/km.

2) Digging: To bury the cable can cost up to 5 ECU/m. If you can use a plough the cost will decrease to 2 ECU/m. To cross a road or a brook makes a minimum of 500 ECU extra.

3) Transformers: The prices of the transformers are about:

300 kW	5 300 ECU
500 kW	6 900 ECU
800 kW	8 900 ECU
1000 kW	10 500 ECU

4) Stations: An ordinary customary concrete station costs about 15 kECU. A simple metal-sheet station amounts to 10 kECU.

A pylon-transformer at 200 kW costs about 8 400 ECU incl. the pylon. There is no need for a building.

3.2 EXAMPLES OF COSTS OF CONNECTIONS TO LOCAL GRID

Example 1: Connection of a 225 kW wind turbine to a transformer, with a free compartment. The distance is 200 m. The cable can be ploughed down. According to DAMP a 240 mm² aluminium cable

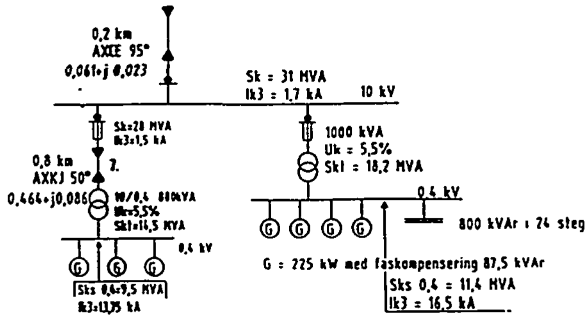

Fig. 1. Connection of a wind park with 7 wind turbines to the 10 kV grid .

should be used. The connection cost is 5.6 kECU or 3 % of the total investment (190 kECU).

Example 2: A 600 kW wind turbin connected to the 10 kV grid. The distance is 500 m. With a metal-sheet station and an 800 kW transformer it amounts to 31 kECU which makes 7 % of the total costs (420 kECU).

Example 3: A wind park with seven 225 kW to the 10 kV grid, fig. 1. It is provided with a central capacitor bank for phase compensation. The park is close to a 10-kW power line. The costs include a building for computer supervision. The connection cost is 4 % of a total investment of 1 400 kECU.

3.3 STRENGTHENING OF THE LOCAL AND REGIONAL GRIDS

Strengthening of the grids will be required when building wind turbines in a larger scale.

On the island of Gotland the utility has put an extra charge on the connection of wind turbines, besides the direct costs. It amounts to 53 ECU/kW. The island of Gotland has the most wind turbines of all districts in Sweden. It is estimated that at the turn of the year 95/96 10 % of the electric power will come from wind turbines. If all inquiries for a grid connection of wind turbines will be realized, the electricity need of the island will be fulfilled to more than 100 %. But already during the next summer the production of wind power electricity in a stormy summer night can be larger than the consumption on the island as a whole. That will be a problem. Now Gotland is supplied by an HVDC cable. The power can only flow in one direction of the cable, due to the existing control system. There is no agreement reached yet about who is going to pay for the rebuilding.

On Gotland they have already begun to strengthen the 10 - 130 kV power lines. Today it seems that the connection charge paid will cover the costs for the strengthening of the grid. The charges are about 4 - 8 % of the total costs for the wind turbines. That can be a guideline for the costs to strengthen the local and regional grids even in other districts, when the connection of wind turbines increases.

3.4 STRENGTHENING OF TRUNK LINES SYSTEMS

In [5] the increased costs for the 400 kV grid, in case of introducing wind power, are discussed. With 2 TWh 1995/97 and 5 TWh in 2010 within the Swedish network, the costs will increase by 2 - 3 % based on a production cost of 3.5 ECUcents/kWh.

The total integration costs according to [5] will be 7 % and 12 %, respectively, at these levels.

4 OTHER SYSTEMS

4.1 OFFSHORE WIND TURBINES

The first wind park in the world offshore in Vindeby, Lolland, Denmark, was 83 % more expensive than the same park on land. An important reason for the extra expenses was the costs for the connection to the grid by means of a sea cable. The owner of the Vindebypark estimates that the next park will only be 57 % more expensive than a park on land. Much of the saving is due to a more efficient and less expensive connection to the grid. This is an area for further development.

4.2 SMALL HOUSE AND FARM WIND TURBINES

A new interest in small wind turbines, 4 - 30 kW, has aroused lately. Although small, they can give a contribution to the energy supply, if many are built. One reason is that they can be easily connected to the grid. On principle, they can be connected to the owner's present electricity supply and diminish the purchase of electricity. If the production becomes larger than the needs, the electricity meter could reverse. That is not in accordance with the Swedish recommendations in TAMP. They state two back-blocked electricity meters, one for each direction. The costs for it takes a considerable part of the profit. With better conditions for measurement andconnection the small wind turbines can become competitive, thanks to that there are no needs for strengthening the grid on no voltage level.

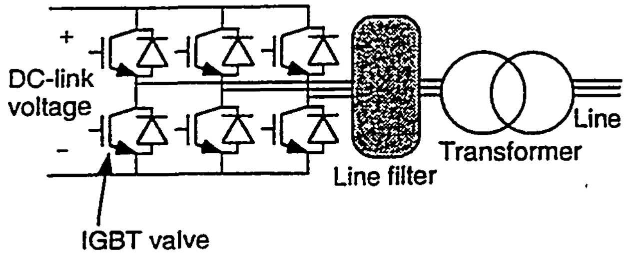

Fig. 2. Schematic figure of a force-commutated inverter.

5 POSSIBLE PROGRESS IN THE FUTURE

There are opportunities to make the connecting to the grid more efficient. Here are some examples:

New electrical systems for wind turbines will give less disturbance on the grid. A Danish manufacturer has a system called "opti-slip", which allows the speed of the wind turbine to increase by 10 % at a gust of wind, and the power production will become much smoother.

At variable-speed operation the wind turbines are connected to the grid via an inverter. In a force-commutated inverter, fig. 2, it is possible to freely choose when to turn on and when to turn off the valves. This possibility means that the force-commutated inverter can create its own three-phase system and when it is connected to the grid, the inverter can freely choose which power factor to use. The inverter can even improve the power quality of the grid.

A German manufacturer states that their 500 kW wind turbine, with variable speed operation, will not give any flickering problem with a short-circuit value at 3.718 MVA. It is about 7 times the rated power. Compare with the recommendation in DAMP, which is 20 times the rated power.

It is possible to place the transformer and the electricity meter inside the tower. Some manufacturers have already begun doing that. It will be appropriate to use a dry insulated tranformer to avoid formation of gases and risks for explosion.

It is possible to use a higher voltage. The current and the voltage drop will decrease, and the power losses in the transformer and cable will be reduced, thinner cables may, therefore, be used. With the wind turbines of current interest, about 600 kW, it is no profit to use medium voltage. The cost of devices for protection and coupling will be much higher.

Most wind turbines are today equipped with a soft starter to diminish the inrush current. If you use soft starter to switch in the capacitor banks, disturbances in the electrical network will be avoided.

It is possible to use the capacitor banks to get fewer slow voltage fluctuations on the grid when the power production from the wind turbines varies. This measure increases the possibility of connecting wind turbines to existing distribution transformers.

It is possible to use the wind turbine control system, i. e. in wind turbines with pitch-control to limit the power output, if there is a risk for high temperature in a cable or a transformer. This measure makes it possible to connect an increased number of wind turbines to the same power line.

The Swedish DAMP recommendations have a rather good margin for transformers. They are based on the risk of high in-rush currents. With the soft starters which all new wind turbines are equipped with today, the risk is eliminated. It is hardly necessary to select a transformer with a higher rated apparent power than the apparent power of the connected wind turbine including capacitor banks.

6 CONCLUSIONS

If the distances for connection are limited the costs for grid connection of wind turbines in Sweden have been about 3 - 8 %. In the future, about the same costs will be added for the strenghtening of local and regional grids. Up to 5 TWh/year within the Swedish network the costs for the strenghtening of the national trunk grid are estimated to 2 - 3 %. It is important that agreements are made, about how to pay for strengthening of the grid. Otherwise it can become an obstacle when building new wind turbines.

New improved electrical systems in the wind turbines give less disturbances on the grid and a better power quality. It is essential to measure quality factors and see how the improved system can impact on the grid connection. By the use of new improved electrical systems, the grid connection ought to be simplified and less expensive.

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ON MINIMIZING THE COST OF WIND TURBINE GRID CONNECTION

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Abstract

The capital cost of grid connecting a wind turbine or farm can be the factor tipping the balance between investment profit and loss. The connection cost is very dependent on the nearby presence of an sufficiently stiff point of interconnection as the cost of new feeder capacity is substantial, typically above 20.000 ECU/km at medium voltage (10 kV) level.

Sufficiently stiff interconnection points for today's large wind turbines can only be found at the voltage levels above the low voltage grid (0.4 kV), and typically, wind turbines are connected to existing medium voltage feeders. However, as for maintaining the power quality to the consumers, only a certain amount of wind power can be connected. In large interconnected power systems the limiting factor for connecting wind power is typically associated with keeping the feeder voltage profile within the acceptable level.

In feeders with wind turbines the stationary minimum voltages will occur in case of maximum consumer loads and no wind power, and the stationary maximum voltages will occur in case of minimum consumer loads and maximum wind power. As to avoid unacceptable stationary voltages during these "extreme" load and production situations, either the feeder must be designed for these, or these situations must be avoided by introducing load and/or production management. Assuming wind turbines to be installed with automatic voltage controlled cut-out and cut-in or more advanced voltage controlled production management such as pitching of the wind turbine blades, the maximum voltage may be kept below the acceptable level without reinforcement of the grid, but on the cost of loosing some of the energy production. At certain assumptions, it may be cost effective to accept wind power production losses for saving grid reinforcement investments.

Probabilistic load flow analyses can indicate the probability for critical stationary voltages, and can be used for evaluating the impact of actions taken as to maintain the voltage within the acceptable limits, i.e. grid reinforcement and/or active load/production management.

The probabilistic approach is illustrated by a fictive, but realistic example. A number of wind turbines are to be installed and connected to an existing 10 kV feeder. The wind power capacity will be so high that the feeder either has to be reinforced or the wind turbines output must be limited during hours with low consumer loads in order to keep the grid voltages at the acceptable level. In the example, the consumer loads and wind power production are statistically described and probabilistic load flow analyses are prepared for a range of grid reinforcement options. The example demonstrates that grid connection costs can be minimized by stopping wind turbines for avoiding unacceptable high voltages as an alternative to grid reinforcement.

THE AVOIDED EXTERNAL COSTS OF USING WIND ENERGY

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Abstract: This paper discusses the external costs of electricity generated by conventional fossil fuel sources, such as coal and nuclear power. It compares the costs of electricity generated with coal with that generated with wind. A measure of the benefits of wind energy is the difference between these two external costs. The methodology used for the estimation of the external costs, as well as the estimates of these costs, are taken from the EC ExternE study, financed by DGXII of the European Commission. The present author was a lead economist for that study.

1. INTRODUCTION

In recent years there has been a great deal of interest in the **external** costs of electricity generation. These are costs borne by society as a result of the generation of electricity, but which are not borne by the producers of that electricity. Examples include the health costs of air pollution produced by coal fired boilers, the impacts on natural eco-systems of the construction of hydropower dams, the noise resulting from wind farms and so on.

Once one takes account of such costs, the 'economics' of electricity generation can change substantially. Generation from renewable sources such as wind has a higher direct cost than generation from fossil fuels such as coal. But the external costs of the latter are much higher, and therefore the **social** costs (the sum of the direct and external costs) may in fact favour renewables, at least in certain circumstances.

In view of this, it is extremely important to estimate the external costs of all sources of electricity generation, both conventional and renewable. Within the EU, the need to value externalities in monetary terms has been expressed in various documents. It is noted in the 5th Environmental Action Programme [1], which is concerned to 'internalise' these externalities by including the external costs in the prices. This position is reiterated in the Commission's White Paper [2]. Finally the EC's proposal to introduce an energy-carbon tax [3] were an attempt to internalise external costs, at least in part, in the pricing of energy in Europe.

1.1 STUDIES OF EXTERNAL COSTS

There are a number of studies that have attempted to measure the external costs of different sources, particularly those associated with conventional sources. Two methodological approaches have been used in this estimation. They can be described as the 'top down' and the 'bottom up' approaches. The top down uses highly aggregated data, for example national emissions and impact data, to estimate the damages associated with particular pollutants. This methodology predominates in most published studies. It has relatively low data requirements, and may give reasonable estimates for average damage costs. The methodology is not, however, appropriate for the estimation of **marginal** costs -- i.e. the costs arising from an increase in the generation of electricity from a particular source.

Examples of the top down approach are [4], [5], [6], [7], and [8].

Hohmeyer's study [4] is certainly one of the first important attempts to estimate externalities. He used a "top-down" approach. First, he identified other studies' estimates of the total damages (health costs for example) attributed to air pollution. Next he estimated the fraction of the total emissions that are from electric power generation with fossil fuels (e.g., 28 percent). Then, he multiplied this fraction by the health costs attributed to air pollution. The result is an 'estimate' of the health damages from fossil fuels. Hohmeyer's methodology enables him to assess "the big picture", but the methodology relies heavily on approximations and previous estimates of total damages. Furthermore it does not take account of the different stages of the fuel cycles, thus ignoring some important sources of external effects. Finally it cannot provide a tool for assessing site-specific effects, which may be very important.

Another well-known study is by Pace University [5]. It used a bottom-up approach to: (i) estimate the emissions and their amounts, (ii) estimate the dispersal of the pollutants, (iii) determine the population, flora and fauna exposed to the pollutants, (iv) estimate the impacts on the population from exposure to the pollutants, and (v) compute the monetary cost of that impact. Pace relied entirely on numerical estimates from previous studies; and used those values to compute damages.

Pearce et al. [6] recently completed a study similar in spirit to the Pace study, and drew quite heavily on the latter. However, by taking a fuel cycle approach, they addressed more impacts than Pace. In none of these cases were data collected at the primary level. Thus these studies are not site specific and do not take account of differences in external costs that arise from differences in topography or concentrations of population.

Unlike the other studies mentioned above, and as part of a different approach, Bernow et al. [6] of the Tellus Institute point out that it is difficult to estimate social costs based on damages. They suggest that abatement costs may be a reasonable surrogate for damages. In this approach, existing and proposed environmental regulations are analyzed to estimate the value that society implicitly places on different environmental impacts. According to Tellus, the marginal cost of abating emissions, when they are at the limit imposed by regulation, reflects the preference of regulators to require that particular level of abatement and the corresponding incremental cost, rather than allow emissions to exceed that limit and subsequently to have adverse impact on the public. The reasoning used by Tellus is that since these regulators represent the public, their views represent the costs placed on those emissions by the public.

The author takes the view that such reasoning is flawed. The premise that marginal control costs represent the costs of air emissions to society implies that regulators know what individual environmental damages are and always decide on the optimal policy where the marginal costs of control equal the marginal damages. In fact it is quite clear that they do not know these costs, and the political processes by which policy decisions are made do not generally have the property that they equate social damages to costs of abatement.

In contrast to this top down approach, the bottom up methodology uses technology specific emissions data for specific power plants, at specific locations. This is used with pollution dispersion models, detailed information on the location of receptors and 'dose-response' functions that link the concentrations of pollutants to impacts on health, property etc. These impacts are valued using techniques described below.

2. THE EXTERNE STUDY

The ExternE study, which was launched in 1991, was intended to be a comprehensive bottom up study of the external costs of electricity generation. It goes beyond the earlier approaches in several respects. These are:

(a) A more thorough characterization of the energy technologies and their discharges into the environment on a site specific basis. Clearly the environmental impacts of electric power generation will vary according to the technology adopted. These need to be made much more precise than has been done in the past before valuations can be carried out. Furthermore, the impacts will vary according to where the plant is located. On *a priori* grounds, site specific differences should be important. This study aims to find out how important these differences are by evaluating the damages from plants with the same technology but with different locations.

(b) A consideration of all major stages of a fuel cycle, rather than just electric power generation. Significant environmental impacts occur during the mining of fuels, their transportation and the eventual disposal of the wastes. These need to be evaluated as carefully as those of the generating stage but so far little work has been done on them.

(c) Modelling the dispersion and transformation of pollutants rather than relying on previous estimates. Existing work has relied mainly on short distance dispersion models for the majority of the air pollution impacts. However, these are inadequate. This study shows that it is necessary to estimate dispersion over much larger distances of the majority of the impacts are to be picked up. Furthermore, the transformation of pollutants needs further attention. There are no adequate models, for example, to analyze the creation of ozone in electric power generation from nitrous oxides and hydrocarbons, and its subsequent dispersion.

(d) Engaging in a more extensive, critical review and use of the ecology, health sciences, and economics literatures than previous studies. As stated earlier, there are many ecological, epidemiological and valuation studies that have come out in the last five to ten years. The ExternE study has reviewed these and used the latest information available in developing its impact pathways and in valuing them.

(e) Estimating externalities by accounting for existing market, regulatory, insurance and other conditions that internalize some damages so that they are not externalities.

Although the ExternE study makes several important advances, it still does not deal with a number of issues and it makes a number of simplifying assumptions. The most important is the fact that it does not look at the power system as whole but rather at the operations of individual plants within that system. Thus, for example, it is assumed that the additional generating capacity that is being evaluated will leave the dispatch of the utility system and associated transmission and distribution requirements unaffected. Accounting for system-wide effects would require running the entire system and looking at the changes in impacts arising from the operation of the modified system. This has not been attempted. A second assumption is that, although the impacts of the additional construction facilities for the plant are included in the analysis, the examples used assume no new roads will have to be built, or new mines opened to allow for the impacts of the additional plant. Third, it does not look at the indirect impacts of the fuel cycle, except in the case of fuel cycles for renewable energy sources such as wind and solar power; and for energy conservation. This means, for example, that it does not assess the environmental costs of producing the cement to construct a generating plant. Such impacts were examined by both the EC and US teams in some preliminary work, but it was found that they were very small; at least two orders of magnitude smaller than the direct emissions For this reason they were ignored in the fossil and nuclear fuel cycles. The same does not hold, however, when the secondary processes and outputs would not have been produced were it not for the fuel cycle (as in the case of the production of certain chemicals for the production of solar cells), or when the second order effects are the dominant external effects (as in the case of energy conservation). For these special cases indirect effects have been analyzed.

The fuel cycles being analyzed in this study are: coal, nuclear, natural gas, oil, lignite, biomass, waste incineration, hydro, wind, solar and energy conservation. The work is ongoing on all the fuel cycles but the preliminary work is complete on most of the fuel cycles.

2.1 PRINCIPLES OF ESTIMATION OF EXTERNAL COSTS IN THE EXTERNE STUDY

At the outset of the ExternE study, certain general principles were recognized as being important in determining the scope of the valuation. These were: comprehensiveness, consistency, transparency, and practicality. It was agreed that the analysis should be comprehensive, in that it should incorporate all the environmental externalities of importance. Since the time period over which these impacts manifest themselves will vary, one cannot impose a single time scale on all environmental impacts. Second, it was decided that the methodology should not be open to the criticism that different fuel cycles have treated the same impact differently. This meant that the same time scale should be implemented for a given physical impact, irrespective of the fuel cycle over which it is being measured. Third, whatever assumptions have been made about the operation of the technology and the nature of the impact, should be clear and transparent, so that sensitivity to different assumptions can be carried out if necessary. Finally all these requirements have to be tempered by the need to maintain a practical approach. Since this study will not be conducting basic research on the physical impacts, it will have to rely on what has been carried out in the many hundreds of research projects in several countries. The time scale of these will vary. Often the impacts will only refer to the immediate consequences. In some cases no clear time scale will have been specified. Given this mixed collection of basic data, it is necessary to accept that the analysis will be limited by what can be determined from the existing data.

The basic philosophy underlying the valuation is based on individual preferences, which are expressed through the willingness to pay (WTP) for something that improves individual welfare, and willingness to accept payment (WTA) for something that reduces individual welfare. The total value of environmental impacts is taken as the sum of the WTP or WTA of the individuals comprising it. Thus no special weight is given to any particular group. This approach contrasts, for example, with that of values based on expert opinion, or values based on the costs of making good any damage done to the environment by the fuel cycle. As was explained earlier, mitigation costs will only provide a valid measure of cost if society is collectively willing to pay for the mitigation, rather than suffer the damage. In such cases mitigation based estimates can provide important values, and have in fact been used in the study in selected areas. However, the validity of that use is dependent on the assumption that society is willing to pay for the mitigation.

The WTP/WTA numbers can be expressed for a number of categories of value. The most important distinction is between values arising from the use of the environment by the individual and values that arise even when there is no identifiable use made of that environment. These are called **use values** and **non-use values** respectively. Non-use values are also sometimes referred to as **existence values.**

Within the category of use values there are many different categories. **Direct use values** arise when an individual makes use of the environment (e.g. s/he breathes the air) and derives a loss of welfare if that environment is polluted. **Indirect use values** arise when an individual's welfare is affected by what happens to another individual. For example, if I feel a loss of welfare as a result of the death or illness of a friend or relation, resulting from increased levels of air pollution, then this loss of welfare translates into a cost through my WTP. It can and has been measured in limited cases and is referred to as an **altruistic value.** Both direct and indirect use values have a time dimension; an environmental change today can result in such values now and in the future.

Another category of use value that is potentially important is that of **option value.** This arises when a action taken now can result in a change in the supply or availability of some environmental good in the future. For example, flooding a region to impound water for a hydro project would result in that area not being available for hiking. A person might have a WTP for the option to use that hiking area, even if s/he was not sure that it would be used. This WTP is the sum of the expected gain in welfare from the use of the area, plus a certain gain in welfare from the knowledge that s/he could use it even if it is not actually used. The latter is referred to as the option value. The literature on environmental valuation shows that, in certain cases the option value will be positive but in general it is not an important category of value (see [9]. There are very few estimates of such values, and in the context of the fuel cycle study it was felt that estimating future use values was difficult enough; estimating option values was not considered an important category to address.

The last category of value is non-use value. This is a controversial category, although values deriving from the existence of a pristine environment are real enough, even for those who never make any use of it. In some respects what constitutes 'use' and what constitutes 'non-use' is not clear. If someone sees a programme about a wilderness area but never visits it, that represents a use value, however indirect. Pure non-use value must not involve any welfare from any sensory experience related to the item being valued. In fact some environmentalists argue that such non-use or existence values are unrelated to human appreciation or otherwise of the environment, but are embedded in, or intrinsic to, the things being valued. For a sympathetic review of this position, see the discussion on the 'new naturalist ethics' [10]. However, that is not the position taken in this study. The basis of valuation remains therefore an anthropocentric one which, however, many economists argue, does not imply an anti-environmentalist stance.

The difficulty in defining non-use values extends, not unnaturally, to measuring them. The only method available for this category is that of the questionnaire approach, or contingent valuation, which is described below. This method has been tested and improved extensively in the past 20 years, and the general consensus is that the technique works effectively where 'market conditions' of exchange can be simulated effectively and where the respondent has considerable familiarity with the item being valued. For most categories of non-use value this is simply not the case. Hence, for the present, non-use values are extremely difficult to value with any accuracy.

Although the valuation of environmental impacts using money values is widespread and growing, there are still many people who find the idea strange at best and distasteful and unacceptable at worst. Given the central role being played by monetary valuation in this exercise, a justification of the method is warranted.

One objection often voiced in the use of WTP is that it is 'income constrained'. Since you cannot pay what you do not have, a poorer person's WTP is less than that of a richer person, other things being equal. This occurs most forcefully in connection with the valuation of a statistical life (VOSL) (which is discussed in greater detail below), where the WTP to avoid an increase in the risk of death is measured in terms of a VOSL. In general one would expect the VOSL for a poor person to be less than that of a rich person. But this is no more or less objectionable than saying that a rich person can and does spend more on health protection than a poor person; or that individuals of higher social status and wealth live longer on average than person of lower status; or that better neighbourhoods will spend more on environmental protection than poorer neighbourhoods. The basic inequalities in society result in different values being put on the environment by different people. One may object to these inequalities, and make a strong case to change them but, as long as they are there, one has to accept the consequences. One could argue, for example, that increased expenditure on high technology medicine in Europe is unethical, even though the citizens of that region have a WTP that justifies such expenditures, because the same expenditure on preventative medicine in a poor developing country would save more lives. However, society does not accept such an argument, taking the view that most decisions about allocation of resources are predicated on the existing inequality of income and wealth, both between and within societies.

This raises a related issue that has arisen in the ExternE study and that is to do with the spatial range over which the values should be measured. An increase in air emissions in one place in Europe certainly has an impact all over Europe, but may also affect other continents. Whose environmental costs should be valued? For most policy purposes it is important to know the costs of all groups affected and so the estimation methodology should be no respecter of national or even continental boundaries. However, it is also true that not all costs will have equal relevance to all decisions. With respect to global warming, for example, European governments will devise an accommodation or protection strategy based on the likely costs in Europe. Hence these should be calculated separately from the costs to other regions of the world. Furthermore, some costs are difficult to assess. If a European power station operates on imported South African coal, or uses imported Nigerian oil, how much of the external costs in mining, drilling etc., should be included? Again, in principle costs outside the Union could be relevant to some decisions -- e.g. Union importation policy, but possibly not to others -- e.g. environmental charges imposed on European private generators.

In practice, it is impossible to measure all such external costs outside Europe for reasons of lack of data. Practical issues of where lines have to be drawn are discussed in [11]. The principle, however, remains that such costs are of interest and relevance to policy makers, although they are not all equally releavant to all decisions.

2.2 TECHNOLOGIES

Energy supply technologies have an operating lifetime of many years, with environmental consequences over an even longer period. The basic question is, what impacts are to be quantified; those of running the plant for a limited period, such as a year, or running it for its lifetime? Estimating the impact over a specified period such as a year has the advantage of being able to trace the effects more fully. It also has the advantage that the 'reference environment' is more easily defined. It should be noted that analyzing the impacts of operating a plant for one year does not imply that the impacts will also be looked at for that period - the latter will be spread out over time and it would be incorrect to restrict oneself to the same time horizon over which the operation is being measured. For example with the nuclear fuel cycle, a plant may have a lifetime of 30 years. However, even looking at the impacts of low-level normal radiation, one has to allow for a period of over 130 years, so that the health impacts of any infants born in the last year of the operation of the plant can be traced through over their normal expected lifetime.

The disadvantage of looking at a limited period is that some of the environmental impacts arise at the beginning and end of the operating life of the technology (e.g., construction and decommissioning). Allowing for these would be difficult in the context of a one-year operating framework. The policy-relevant question that needs to be answered is what social cost does the operation of this technology impose on society? In order to answer that, it is necessary to look at the operations over the lifetime. It may also be desirable to know what the external costs associated with the construction and decommissioning are, separately from those of operation. By this means it would be possible to impose an 'environmental charge' on the different groups responsible for the different operating stages. However, this too will require a lifetime analysis to be carried out, and hence it was decided that a lifetime approach be taken to the operation of the main technology.

This decision is modified when looking at the operation of the technologies upstream and downstream of the main technology -- mining, waste disposal, etc. Here the relevant period is determined by the operating period of the main technology.

The identification of an appropriate lifetime may be problematic, as the economic lifetime differs from the physical lifetime, due to changing economic conditions and the development of new technologies. To avoid complications and to retain a consistency across comparisons, it was decided that the lifetime taken should be the design lifetime. If in future applications of the fuel cycles it is decided that a shorter operating period is appropriate, the methodology should be set up in such a way that a calculation of the costs over the shorter period can be prepared.

2.3 IMPACTS

The impacts of a particular operation take place over periods as short as the operating period itself (e.g., noise, odour), to others that last for hundreds or even thousands of years (e.g., recovery of soil from acidification, disposal of radioactive waste). In principle each impact should be traced through for as long as it is considered to be relevant to the human welfare. No arbitrary limit should be imposed, such as saying that when X% of the potential damages are assessed, the analysis will be terminated. In practice, this process can be limited by: (a) uncertainty about the physical impacts in the distant future, and (b) difficulty in defining a reference environment.

The methodology is based on taking the difference between the environment without the operation under consideration, and with it. However, difficulties in defining the without-operation case (i.e., the reference environment) are very real. The relevant variables in describing the reference environment include background levels of emissions and other environment characteristics, as well as socioeconomic variables, such as age and composition of the population under risk. Beyond a period of 20 years or thereabouts, such projections are virtually impossible make with any certainty. At the same time, it is essential to look periods longer than 20 years. For example, if a particular operation results in the irreversible loss of recreational land, the value of that loss is the stream of benefits that it would have generated over an infinite period of time. These benefits will, in turn, depend on the number of visitors using that site, and their individual valuation of the benefits, which depend on real incomes. Hence some assumptions have to be made about these variables. Although it is not possible to assume in all cases that the 'economic conditions will remain as they are now', often that is the only practicable assumption that can be made. In much of the evaluation of the long term impacts that indeed is what was done.

2.4 DAMAGES

It was decided that damages would be valued over the maximum time scale feasible. This could involve an even longer time frame than the impacts stage. However limitations of existing knowledge and data availability from existing studies limited the time period that could be considered.

2.5 DISCOUNTING

Discounting is the practice of placing lower numerical values on future benefits and costs as compared to present benefits and costs. In the valuation of environmental impacts of electricity generation it is an important issue because many of the environmental damages of present actions will occur many years from now and the higher the discount rate, the lower the value that will be attached to these damages. This can have major implications for policy.

One environmental critique of discounting relates to compensation across generations. Suppose an investment today would cause environmental damages of ECU X, T years from now. The argument for representing this damage in discounted terms by the amount ECU $X/(i+r)^T$ is the following. If this latter amount were invested at the opportunity cost of capital discount rate r, it would amount to ECU X in T years time. This could then be used to compensate those who suffer the damages in that year. In [12] it is argued, however, that using the discounted value is only legitimate if the compensation is <u>actually</u> paid. Otherwise, he argues, we cannot represent those damages by a discounted cost.

The problem in both cases is that actual and 'potential' compensation are being confused. The fact that there is a sum that could be generated by the project and that could be used for the <u>potential</u> compensation of the victim is enough to ensure its efficiency. Whether the investment is made and whether compensation is <u>actually</u> carried out is a separate question and one which is not relevant to the issue of how to choose a discount rate.

Related to these criticisms, however, is a very real issue. In some cases the investment fund needs to be held for very long periods before the potential compensation becomes due. With some forms of nuclear waste the period could run into thousands of years. Human experience with capital investments and their rates of return does not run into more than a couple of hundred years at the most. To give an example, if 1 ECU were invested today a real rate of return of 7 percent per annum, it would amount to nearly ECU 491 trillion in 500 years time. Such amounts are inconceivable and it is not reasonable to base decisions to protect future generations on them. In the ExternE project this issue had to be grappled with. It became evident quite quickly that where future damages were occurring very far into the future, the use of discount rates did not offer a reasonable way of dealing with them. At any positive rate the costs became insignificant and a zero rate they were so large as to dominate all the calculations. One possible solution is to define the rights of future generations and use those to circumscribe the options in terms of what impacts can be imposed on them.

The ExternE study was unable to resolve these problems. Based on considerations of the underlying rates of time preference, rate of economic growth etc. a central discount rate of 3% was chosen. In order to test the sensitivity of the solution to the discount rate, the calculation of external costs were also made for discount rates of 0 and 10 percent. This provides some guide of how important the discount rate is, but does not, of course, help in the choice of that rate.

2.6 UNCERTAINTY

Uncertainty in its various manifestations is arguably the most important and least satisfactorily-addressed aspect of the whole assessment of the environmental impacts of fuel cycles (not just the economic component). There are two distinct aspects of the uncertainty. One is the uncertainty about the different parameters of the impact pathway, including the monetary valuation; and the other is the impact of uncertainty on the valuation of impacts, such as accidents, risks of disease etc. In the ExternE study it was noted that overall uncertainty is the product of uncertainty in each of the four stages of the impact pathway: estimation of emissions, calculation of the spatial dispersion of the emissions, estimation of the physical impact of the dispersed pollutants, and valuation of these impacts. If one could quantify the uncertainty at each of these stages, one could quantify the overall uncertainty in terms of some probability distribution. However, it is not generally possible to quantify the uncertainty in terms of probability distributions. A French application of the ExternE methodology looked at a special case where the underlying distribution is assumed to be lognormal and some subjective estimates are made of the geometric standard deviation of that distribution [13]. In that special case it is possible to arrive at confidence intervals for the damage estimates.

Unfortunately this model cannot always be applied, and hence the standard treatment of uncertainty in the study has been to take a scenario approach. A 'base case' value for each key parameter is combined with low and high case scenarios. As a rough guide, the high case scenarios could take estimates of parameters 100% higher than the base case, and the low case scenarios could take values 50% of the base case. If this is done for each component of the valuation cycle where there is a parameter that is relevant, and for which there is no better estimate of the range of uncertainty the overall impact on the final estimated external costs will be correspondingly larger. This does not provide a statistically valid estimate of the range of values for the external costs, with a given confidence interval, or resolve the uncertainty issue, but it will be a useful indication of where they lie.

2.7 TRANSFERABILITY OF ESTIMATES OF ENVIRONMENTAL DAMAGE

The environmental damages associated with a particular fuel cycle will depend on which plant is being considered and when that plant is being operated. Clearly, however, it would be infeasible to estimate all environmental damages for each location and time specific fuel cycle *ab initio*. Much of the work required is extremely time consuming and expensive, making the transfer of estimates from one study to another an important part of the exercise. The difficult is to know when a damage estimate is transferable and what modifications, if any, need to be made before it can be used in its new context.

Benefit transfer is "an application of monetary values from a particular valuation study to an alternative or secondary policy decision setting, often in another geographic area than the one where the original study was performed" [14]. There are three main biases inherent in transferring benefits to other areas:

(a) Original data sets vary from those in the place of application, and the problems inherent in non-market valuation methods are magnified if transferring to another area.

(b) Monetary estimates are often stated in units other than the impacts. For example, dose response functions may estimate mortality (reduced fish populations) while benefit estimates are based on behavioural changes (reduced angling days). The linkage between these two units must be established to enable damage estimation.

(c) Studies most often estimate benefits in average, non-marginal terms and do not use methods designed to be transferable in terms of site, region and population characteristics.

Benefit transfer application can be based on: (a) expert opinion, or (b) meta analysis. Expert opinion looks at the reasonableness involved in making the transfer and in determining what modifications or proxies are needed to make the transfer more accurate. In many cases expert opinion has been resorted to in making the benefit transfer during the ExternE study. In general the more 'conditional' the original data estimates (e.g. damages per person, per unit of dispersed pollution, for a given age distribution) the better the benefit transfer will be.

Where several studies, reporting a similar final estimate of environmental damage, exist, and where there are significant differences between them in terms of the background variables, a procedure known as meta-analysis has been developed to transfer the results from one study across to other applications. What such an analysis does is to take the estimated damages from a range of studies of, for example, coal fired plants and see how they vary systematically, according to affected population, building areas, crops, level of income of the population, etc. The analysis is carried out using econometric techniques, which yield estimates of the responsiveness of damages to the various factors that render them more transferable across situations. This can then be used to derive a simple formula relating environmental costs to per capita income, which could then be employed to calculate damages in countries where no relevant studies were available.

Estimates of damages based on meta-analysis have been provided in a formal sense in a study carried out in the US on air pollution [15], where it was found that damages per unit of concentration vary inversely with the average price of property in the study (the higher the price the lower the unit value of damage). If correct, it would enable an adjustment to the estimated value to be made on the basis of the average prices of properties in the area being investigated. A formal meta-analysis is difficult to carry out, and has not proved possible in the ExternE study. However, some of the "expert" adjustments do make an informal meta analysis. For example, adjusting estimates of damages for size of population to obtain a per capita estimate and transferring that to the new study implicitly assumes that damages are proportional to population. Such adjustments are frequently made.

3. ESTIMATION OF SPECIFIC EXTERNAL COSTS -- COAL FUEL CYCLE

In this and the next section the main estimates of damages for the coal and wind fuel cycles are reported. For each cycle the details of the estimation procedure are given in [16] and [17] res[ectively.

The coal fuel cycle was evaluated for two sites: one in Germany and in the United Kingdom. The sites and technologies used are typical for coal fired power stations commissioned in 1990. For the UK the site chosen was West Burton, where an 1800MW station was planned for but not built. Coal is assumed to be drawn from the mines nearby and has an ash content of 15% and a sulphur content of 1.6%. Limestone for the flue gas desulphurisation plant is assumed to be taken from the nearby peak district of Derbyshire. Both coal and limestone are assumed to be transported to the plant by rail. Waste solids are assumed to be sold for subsequent use in the construction industry or landfilled in a disused quarry nearby.

The German site chosen was near the city of Lauffen, 35km north of Stuttgart in the Bundesland of Baden Wurttemberg. It has a capacity of 7000MW. Coal is taken from the Ruhrgebeit and Saarland coalfields and has ash and sulphur contents of 12% and 1.2% respectively. Waste products are predominantly recycled in compliance with German law - ash on road construction and cement manufacture and gypsum for board making.

In both cases the same technology is used. The coal is pulverised and burnt in large furnaces to produce steam which is then used to generate electricity. There is no use of waste heat and therefore the efficiency is limited to 37.5% (on a higher heating value basis). Both power stations are fitted with FGD units, reducing SO_2 by 90%. However there are differences in emissions of NO_x. The German plant uses a selective catalytic reduction (SCR) system whereas the UK plant operates with low NO_x burners (LNBs), which are less effective. As a result of these factors, and of the different quality of the coal emissions of pollutants per unit of energy differ at the two plants. Table 1 below describes the major emissions.

Table 1 Emissions of Major Pollutants at the Two Coal Plants

Pollutant	Emissions in g/kWh of electricity	
	West Burton	Lauffen
CO_2	880	880
SO_2	1.1	0.8
NO_x	2.2	0.8
Primary Particulates	0.16	0.20

Source: [16]

The stages covered in the analysis are: construction of the plant, coal mining, limestone quarrying, power generation, transmission of electricity to the grid, waste disposal, decommissioning of the plant, transport of the bulk materials and transport of personnel.

3.1 SPECIAL FEATURES OF THE COAL CYCLES

Although most of the issues arising in the valuation of external costs have been discussed above, a number of specific points arose in the coal fuel cycle. These are discussed below.

(a) A number of models were used to estimate the dispersion of pollutants. Short range pollutants were estimated using Gaussian plume models. Longer range dispersion was estimated using several models, including the Harwell Windrose Trajectory Model that tracked sulphur and nitrogen emissions throughout Europe.

(b) The priority impacts that emerged from a preliminary screening were: human health, occupational and public accidents, and impacts on: materials, crops, forests, freshwater fisheries, unmanaged eco-systems, global warming, noise, ground wand surface water quality (from coal mining) and building construction (from coal mining).

(c) Some difficulties arose in the valuation of all impacts. Briefly are summarised below.

3.1.1 HEALTH

The valuation of health impacts can be divided into mortality impacts and morbidity impacts; and into occupational health impacts and public health impacts.

The mortality approach in the valuation literature is based on the estimation of the willingness to pay for a change in the risk of death. This is converted into the 'value of a statistical life' (VOSL) by dividing the WTP by the change in risk. So, for example, if the estimated WTP is ECU 100 for a reduction in the risk of death of 1/10000, the value of a statistical life is estimated at 100*10000, which equals one million ECU.

Several surveys of VOSL studies are available in the literature (See [11] for details). On average, the highest values come from the CVM studies and the lowest from the consumer market studies where actual expenditures are involved. Excluding extreme or unreliable studies, the range of values obtained is ECU 2.0-2.6 mn for the US studies, and ECU 2.5-4.4 mn for the European studies. From this survey it was concluded that, at the present time a figure of ECU 2.6 mn. in 1990 prices appears to be the best central estimate for the VOSL. A further issue that arose in the study was whether to take the same value of VOSL for all countries or adjust the value according to income/living standards etc. Within the EU a single value is taken on the grounds that (a) thereis no evidence to suggest that values vary sytematically across countries and (b) it would be consistent with attempts to harmonize suich things as safety standards, pollution regulations etc. Outside Europe the question is more open. Differences in attidues to risk certainly exist, implying a lower VOSL in poorer countries. However, several researchers on the ECFC team have argued that, in so far as the valuation is to influence EU policies, it is the EU vaue that should be taken. This is in fact what was done for all extra EU impacts, with the exception of global warming. For that impact. results with different values of VOSL as well as a single value were presented, as part of a review of the results of other studies.

For morbidity Impacts, there is an enormous US literature on valuing morbidity effects, and a virtual absence of one in Europe. Given the collaborative nature of this study, the maximum use has been made of the excellent work carried out in this area by the US team, with modifications to their findings as and when appropriate.

The dose response function for morbidity in the epidemiological literature vary from relating cancer, to those that are based on changes in lung function, as measured in laboratory conditions. As the latter are not susceptible to economic valuation they have not been used. Even among the endpoints that could, in principle be valued, there are some that have not been so valued, as will be seen from the survey below.

Valuation is ideally based on WTP, which should encompass the costs of illness borne by the individual, plus any foregone earnings. In addition any social costs of illness should be added. The WTP for an illness is thus composed of the following parts: the value of the time lost because of the illness, the value of the lost utility because of the pain and suffering, and the costs of any expenditures on averting and/or mitigating the effects of the illness. The last category includes both expenditures on prophylactics, as well as on the treatment of the illness once it has occurred. To value these components researchers have estimated the costs of illness directly, and used CVM methods as well as models of avertive behavior to estimate the other components.

The costs of illness (COI) are the easiest to measure, based either on the actual expenditures associated with different illnesses, or on the expected frequency of the use of different services for different illnesses. The costs of lost time are typically valued at the post-tax wage rate (for the work time lost), and at the opportunity cost of leisure (for the leisure time lost). Typically the latter is between one half and one third of the post-tax wage. Complications arise when the worker can work but is not performing at his full capacity. In that case an estimate of the productivity loss has to be made. It is important to note that COI is only a component of the total cost. However, since the other components are difficult to measure, estimates have been made of the relationship between the total WTP and COI. Recent studies, surveyed extensively in the US Coal Fuel Cycle Report, have come up with estimates of 2.0 for asthma, and around 3.0 for a range of other illnesses [18].

CVM is the only approach that can estimate the value of the pain and suffering. The difficulties are those generally associated with the use of CVM and, in addition, allowing for the fact that it is difficult to know which of the many costs are included in the responses that are given. In general respondents will not include those costs that are not borne by them as a result of the illness (e.g., through medical insurance). In that event, such costs need to be added. In this category one should also include the cost, in terms of pain and suffering, that the illness causes to other people (the so-called altruistic cost).

Avertive behavior is the most complex of the three to model. It involves the estimation of a health production function, from which one would be able to estimate the inputs used by the individual in different health states, and taking the difference in value between these obtain the cost of moving from one health state to another. The difficulty is in estimating that function, where many 'inputs' provide more than one service (e.g., bottled water, air conditioners), and where the changes in consumption as a function of the state of illness are difficult to estimate.

The US Fuel Cycle Study provides an extensive list of the empirical literature on the costs of morbidity. The broad groups under which the estimates can be classified are discussed below.

Restrictive Activity Days (RAD): A large number of studies, using Cost of illness (COI) as well as CVM methods have been used to estimate several categories of RADs. Theey are among the easier of the health impacts to value, as they relate to acute events, lasting a well defined period. The US study provides central or best estimates for these impacts which can, as a first approximation, be taken in the European study using a purchasing power parity (PPP) exchange rate. The central estimate obtained for RADs in Europe by this method was ECU 62. It is interesting to note that one French study of RADs (carried out by the French team implementing the Fuel Cycle Study) estimated a value of ECU 49, based on costs of illness alone. If one takes this COI value and grosses-up the value by using the estimated factor of between 2.0 and 3.0 a much higher value is obtained than that of the US studies.

Chronic Illness: The valuation of the chronic illness is largely in terms of the COI approach (although there are a few CVM studies. The COI approach includes the direct as well as the indirect costs of the illness (such as lost earnings and loss of leisure time). The CVM approach operates in terms similar to the value of statistical life (VOSL) - i.e., by asking what the willingness to pay to reduce the risk of contracting a chronic respiratory illness would be. The corresponding value is referred to as the 'value of a statistical case' (or VSC); and the US study [18] quotes other studies which show that the best estimate for the VSC for respiratory disease is around US$ 1 mn. (ECU 0.8 mn., 1990). Given that a central estimate of the VOSL in the US study is around US$ 2.5 mn. (ECU 1.9 mn., 1990), this would suggest that the value of a chronic VSC is around 40% of that of the corresponding VOSL for Europe (i.e. ECU 1 mn.). This can only be an indicative figure but, a first guideline to the values in this area, it is probably not too bad. In due course, more detailed costs should be computed and compared with those that emerge from the use of the 0.4*VOSL valuation (in conjunction with the relevant probabilities). So far, however, the need to estimate VSC for the European context has not arisen as the ExternE study has not evaluated any endpoint in which it was required.

Symptom-Days: The US Fuel Cycle Study reviews the extensive literature on the valuation of symptom-days. These include CVM studies, as well as some that combine avertive behavior and CVM. Although the work carried out is impressive, there are still many difficulties to be resolved. The CVM studies have problems of low response rates and extreme bids that have to be discounted. There is also a difficulty in knowing the extent to which the responses include the use of avertive measures. Some of the results appear to indicate that the latter are not always allowed for. Some recent studies (Dickie et al (1986), (1987)) have included information on actual avertive behaviour and revealed responses but, as the US Fuel Cycle Study points out, "the results of this study need considerable refinement before they can be used with confidence in a morbidity benefit analysis. The limitations arise in the theory, data, statistical, and implementation phases of the study" (ORNL/RFF (1993)). Allowing for all these difficulties, however, the central estimate for a symptom day obtained in the US is $7.9 (ECU 6.3).

Altruistic Impacts: As with symptom-days, estimates of the impact of an illness on the utility of others is not at a stage at which it can be used in a valuation exercise. One US study (Viscusi, Magat and Forrest (1988)) came up with an altruistic value for each case of poisoning avoided of more than 5 times the private valuation. The experiment consisted of a CVM, in which individuals were asked their WTP for a TV campaign that would reduce poisoning resulting from poor handling of insecticides. However, the study had a relatively unsophisticated design and the results need to be confirmed in other studies. Work in the UK by Jones-Lee et al [19] and Needleman [20] has suggested that the altruistic values are around 40-50% of the private total valuations. Again, however, these are isolated findings and need to be corroborated. In view of the current state of the art in this area it was decided that altruistic valuations not be included in the ExternE.

Other Endpoints: The following other endpoints were valued by the US team: Chest Discomfort, Emergency Room Visits (ERV), Respiratory Hospital Admissions (RHA), Children's Bronchitis, Asthma Attacks, Non-fatal Cancers, Severe Hereditary Effects and occupational impacts. For mortality impacts it was decided that the VOSL could be used, although the results would be reported separately. For occupational morbidity impacts, however, the WTP estimates discussed above seemed inappropriate and their valuation is based on the compensation payable to those who suffer from the related diseases as well as some other *ad hoc* assumptions. In particular, the following valuations have been used: workers diseases (simple pneumoconiosis) -- not valued as probability of death is not estimated; accidents -- minor injuries, ECU 420 to 3,400. Serious injuries, ECU 20,000 to 200,000. Both are based on UK Department of Transport estimates (lower end) and Pearce et al.'s speculative estimate for serious injury at the upper end.

In the estimates obtained, the dominant impact has been that of pollutants on acute mortality (i.e. deaths shortly after exposure to increased concentrations). For occupational health the major impacts are of course on coal miners and arise from radon and dust.

Accidents occur at all stages of the coal fuel cycle but again mining accidents are dominant.

3.1.2 MATERIALS

For materials the principal damages are to galvanised steel, paint and mortar resulting from acid corrosion and SO_2. There are however, considerable uncertainties arising from difficulties in establishing an inventory of materials and in estimating the damages, given the corrosion estimates (how does one allow for changes in the materials used, for example)?

3.1.3 CROPS

For crops the major impacts are from ozone, followed by SO_2. Ozone impacts could not be assessed as it is difficult to separate out the marginal impact of power station activities on ozone. For SO_2 the impacts on cereals yields are very small, but the areas affected are very large. Hence total annual losses from either of these stations was estimated at 2000 tonnes. For several crops we do not have adequate dose response functions. The impacts

3.1.4 FORESTS

For forests there are considerable problems relating to the estimation of impacts. Only limited impacts, based on the impacts of exceeding critical loads on the Norway spruce in the case of Germany; and the relationship between acid load exceedence and timber growth in Britain have been estimated. The estimates are acknowledged to be inadequate and more research is needed.

3.1.5 FRESHWATER FISHERIES

For freshwater fisheries, most impacts are very difficult to estimate. Some estimates exist of the effects of higher acidity on brown trout fish stocks. Although these effects have been quantified in physical terms it has not been possible to value them. As an upper bound to some damages, the value of liming certain lakes has been taken as a measure of the cost of increased acidity.

3.1.6 UNMANAGED TERRESTERIAL ECOSYSTEMS

In the case of unmanaged terrestrial ecosystems, several damages have been assessed but not quantified. The ExternE study took the view that, at this stage it was not possible to value, in monetary terms, damages to such ecosystems from individual power plants.

3.1.7 GLOBAL WARMING

Global warming is one of the most difficult impacts to address. The problem is not best handled in a bottom up framework, as the effect of increased greenhouse gases are independent of where or how they are generated. Existing studies of these impacts are based on assumed increases in the profile of greenhouse gases and are extremely uncertain. Moreover they do not provide information on the marginal impact of increases in emissions. As damages from a given increase in emissions at any point in time will themselves be spread out over time, the discount rate is also relevant. At present the 'consensus' is that damages range from 8-23 mECU/kWh with a discount rate of around 1%. If rates of 3 and 10% are used the damages fall to 1.1-3.3 mECU/kWh and 0.3-0.9 mECU/kWh. Consensus is perhaps a misleading term, as all these studies are based on a common set of assumptions, and not all commentators on global warming agree with them. If allowance is made for these more disparate studies we obtain estimates in the range 6-60 mECU/kWh, falling 4-40 mECU/kWh and 0.8-80 mECU/kWh with discount rates of 3 and 10% respectively.

3.1.8 NOISE

Noise damages arise mainly from the transportation of materials, but also from the operation of the plant. By taking the noise footprints of the main sources, and relating them to the value of the properties affected the ExternE study estimated the damages arising from this source. Estimates were only carried out for the UK site.

3.1.9 OTHER IMPACTS

The other impacts of the coal fuel cycle were found to be small enough not to merit estimation. These included possible impacts of coal mining on water quality through leaching of pollutants into groundwater, possible subsidence to buildings as a result of mining, visual intrusion from structures and from air pollution, increased traffic congestion, and impacts of trace metals' emissions.

3.1.10 MAIN RESULTS

The main results of the coal fuel cycle are summarised in Table 2 below. We can take the generation cost of coal fired electricity from a new coal power station with the technology specified in the case of the UK plant, as 39 mECU/kWH, based on UK estimated generation costs. The external costs without global warming add then about 15-25 percent to these direct generating costs. If global warming costs are added, however, the social cost increases to 52-115 mECU/kWh, an increase of 30-188%. **Thus uncertainty about global warming impacts dominates the estimation of the external costs of coal power generation.**

The other uncertainties and differences between the UK and German studies also point to the directions for some future research. The extent of coverage in estimating health impacts has to be regional, at the very least. Even though the impacts are small at long distances from the site, the fact that large numbers are affected means that the total external cost is much larger when the range is extended. Second, a careful evaluation of the materials inventories is required for a proper estimation of that item of external cost. Third, there are many items that have not been quantified. In this sense, the 'total' external cost is an incorrect statement. However, it can be taken as a **minimum cost figure.**

4. THE EXTERNAL COSTS OF WIND GENERATED ELECTRICITY.

This section is based on the ExternE project report [17]. The analysis of wind energy is based on a design having a rated capacity of about 300kW and a turbine diameter of 30 meters. The turbines have two or three blades. The locations for the analysis are in the UK; Delabole in the County of Cornwall and Penrhyddlan in Central Wales. The Delabole wind farm occupies an area of 50 ha. and has 10 turbines 280 meters apart. The turbines are the three bladed Vesta winded 34 machines which operate at speeds of 7.6 m/s to 25 m/s. The estimated annual load factor is 28-30%. IN the second reference environment has two separate wind farms of 42 and 61 turbines. They are located close together, with the minimum distance between them being one km. The two together occupy 300 hectares. The turbines are set in rows of 3-10 machines, with 100 meters between machines and 300 meters between rows. The technology is the Mitsubishi MWT 250 machine with a rated capacity of 300kW, giving the farm a total capacity of 30.9MW. It operates at wind speeds of between 5 m/s and 24 m/s. The average wind speed

Table 2: Summary of External Cost Estimates for the Coal Fuel Cycle

Damage Category	Valuation Estimate (mECU/kWh)		Range	Confidence
	UK (West Burton)	Germany (Lauffen)		
Public Health	4	13	West Burton (UK) Lauffen (Regional)	Low to Medium
Occupational - Health	0.1	0.3	Local	Low to Medium
Occupation - Accidents	0.8	2.0	Local	High
Agriculture	0.03	0.04	Mostly regional	Low to Medium
Timber (1)	0.004	NQ	Regional	Low
Materials (2)	1.3	0.1	Regional	Low to High
Terrestrial Ecosystems	NQ	NQ	Regional	
Marine Ecosystems	NQ	NQ	Regional	
Noise	0.2	NQ	Local	
Subtotal of quantified Impacts	6.2	15.4		
Global Warming (3)	6-60	6-60	Global	Very Low
Total	12.2-60.0	21.4-75.4		

Source: [16]

Notes: 1. Only timber effects on forest eco-systems were valued
2. The difference arise mainly because of the poorer coverage of property in the German case.
3. Excludes the extreme estimates of 5000 mECU/kWH made by Hohmeyer.

at the site is 7.56 m/s and the estimated load factor is 31%.

In contrast to the coal fuel cycle, the wind cycle has been analyzed to take account of the externalities arising from the construction of materials used in the wind farms. The justification is that such costs are an important component of the wind fuel cycle, whereas they make virtually no difference to the external cost estimate in the coal fuel cycle.

The impacts included in the wind fuel cycle are:

- Noise from turbines
- Visual intrusion
- Accident in manufacturing of equipment
- Global warming from materials processing
- Accidents in turbine manufacture
- Impacts of turbines on birds
- Impacts on terrestrial ecosystems
- Electromagnetic interference.

4.2 MAIN IMPACTS OF WIND ENERGY

4.2.1 NOISE

The most important impacts of wind farms are believed to be noise and visual intrusion. The analysis of noise has focused on the operating turbines, which have given rise to numerous complaints from local residents. Although site selection in the UK is based in part on considerations of noise, the government does not impose noise restrictions, such as those operating in Denmark, the Netherlands and Germany. In these three countries, there are upper limits of noise that must not be exceeded. In the ExternE project the additional noise from wind turbines was estimated. The main problem has been mechanical noise rather than aerodynamic noise, which some UK research has shown is not a problem when machines operate to design specifications [21]. To assess the noise impact, first the noise generated at source is estimated. Then a model of noise propagation is used to estimate noise at different points from the source. The ExternE project used the IEA model in which noise at distance r from power source L_w is given by

$$L_r = L_w - 10.\log_{10}(2) - 20.\log_{10}r - þ.r$$

where þ is the coefficient of absorbtion of sound in the air and is a function of frequency as well as temperature, pressure and humidity.

Given the noise at different locations its impact on the overall noise will depend on the background noise level. Hence estimates of background noise are required for an assessment of the marginal noise to be made. The valuation of the additional noise can then be made from valuations of property depreciation associated with noise or from the noise annoyance associated with a given noise increase. The second method comes up with much lower damage estimates (two orders of magnitude lower). Given serious reservations about the annoyance approach it was decided to take the direct property depreciation approach. The resulting estimates of noise damage were 1.1 mECU/kWh for Delabole and 0.07 mECU/kWh for the Welsh site. Lower bounds are 25-30% of the central estimates and upper bounds are 3-4 times higher

4.2.2 VISUAL AMENITY

As is noted in the ExternE report, visual amenity impacts are among the most controversial and the most difficult to quantify. In addition to being intrusive to the landscape, the turbines can produce a 'shadow flicker' as sunlight passes through them. Such stroboscopic impacts can induce attacks in epilepsy sufferers. However, such effects are very local (less than 300 meters) and of very short duration.

The main issue is that the sites which are suitable for wind farms are also often sites of great natural beauty. To a large extent the problem is addressed by the planning procedures under which such sites are protected, but this does not guarantee the complete absence of any visual impacts.

In terms of valuation, the difficulty is that there are no studies of the effects of wind farms on visual amenity. The studies which deal with visual amenity cover such issues as landscape values of national parks, and not the impacts of intrusive factors such as wind farms [22]. In the ExternE study the value attached to preserving the existing landscape was taken as the same as that found in the Willis and Garrod study (ECU35 per annum). Assuming that the benefit transfer is valid this is equivalent to saying that a wind farm would take away all the benefits of enjoying the countryside and landscape and is clearly an overestimate. The above applies to designated national parks. For non-designated areas a speculative estimate of 3.5 ECU has been taken. Using these estimates, and data on the resident population as well as the number of visitors, the study comes up with damage estimates of 1.9 mECU/kWh for the Cornwall site and 0.09 mECU/kWh for the Wales site, the higher Cornwall figure reflecting the larger number of visitors to the area.

4.2.3 OTHER DAMAGES

The other damages that have been quantified are 'secondary damages', resulting from the construction of materials used in the wind farms. The energy used in making these materials in the UK has been taken from existing studies of energy coefficients, and the emissions resulting have been calculated accordingly. The resulting emissions are then valued as explained in Section 3. The final estimates are summarised in Table 3 below. For accidents a similar approach has been taken, with accidents in the mining and transport of the raw materials, in the construction of the equipment and in the operation of the plant being taken from existing statistics and valued as for the coal cycle.

Impacts that have not been valued include impacts on birds. The UK studies indicate no measurable impact to date but warn that proposed sites should be checked for possible impacts. Certainly sites in Spain and California have found some important effects. Other non valued impacts are those on terrestrial ecosystems and electromagnetic interference. Ecosystems are likely to be most affected if the wind farm is located on sites that were not farmed. EIAs undertaken prior to the construction of the wind farm should protect against significant effects. Radio and other communications can be affected by wind farms but again these impacts can be largely avoided be suitable selection of sites. Where some impacts are unavoidable the remedy lies in the provision of alternative broadcasting and communication facilities, the costs of which are borne by the wind farm developer.

4.2.4 THE MAIN RESULTS

The main results are summarised in Table 3 below.

Table 3: Wind Fuel Cycle External Costs Summary

Category	External Cost (mECU/kWh) Cornwall	Wales	Reliability
Noise	1.10	0.07	Medium
Visual Intrusion	1.90	0.90	Low 1/
Global Warming	0.15	0.15	V. Low 2/
Acidification	0.70		Low 3/
Public Accidents	0.09		Medium
Occupat. Accidents	0.26		Medium
TOTAL	4.20	2.17	

1. This estimate is only indicative.
2. On the basis of the discussion in Section 3, Global warming estimates could be 60% lower or 400% higher.
3. These damages are based on the coal fuel cycle costs, wassuming energy is generated from sources without acid gas abatement.

A number of points should be noted. First, the external costs are very site specific. In this analysis the difference between the two sites is 100%. If more sties were included the range would doubtless increase. Second, unlike the case of the coal fuel cycle, most costs are covered in this analysis. Hence the comparison is not quite 'like with like'.

The direct costs of wind power will vary according to site. In an earlier UK study these ranged from 48 mECU/kWH to 159 mECU/kWH. Hence the external costs estimates here would be 5-10 percent of the most efficient sites and 1.5-3 percent of the most expensive sties. (These direct costs may have changed since these earlier estimates).

5. CONCLUSIONS

This paper has reviewed the external costs of coal generated electricity and compared it with those from wind energy. In terms of direct costs, even 'new coal' -- i.e. coal with the modern abatement technologies, is less expensive than the most efficient wind. From the above figures, it is about 9 mECU/kWH less expensive. However, the coal generation has external costs of anything between 8 and 70 mECU/kWH, which reverses the ranking in almost all cases. With more expensive wind plants the ranking is less clear. Taking a medium value of the external costs of coal as around 45 mECU/KwH, wind energy will be justified with direct costs of up to 80 mECU/kWH.

These conclusions must be qualified. Many of the external costs of coal have not been quantified, which suggests that the preference for wind will be even stronger. The upper bounds for some wind external costs reinforces that conclusion. However, wind energy is more site specific than coal power and so the comparisons have to be made on a case by case basis.

ACKNOWLEDGMENT

This paper draws on the work of the whole ExternE team and their contributions must be acknowledged in full. Particular reference must be made to the work of Nick Eyre, who was responsible for the wind energy analysis; but mention should also be made of the work of Mike Holland, Mike Hornung, Fintan Hurley, Wolfram Krewitt, Stale Navrud. None of these persons has, however, seen this paper, which draws some further conclusions about external costs.

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The Role of Wind Energy in the Programm of Power Supply for Northern Russia Territories.

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Abstract: In the paper examined technical, management and economic problems has been arising during working out of above mentioned Pow Supply Programm based on the renewable energy sources usage and proved t leading role of wind energy in this Programm.

INTRODUCTION. The working out of the Programm "Power Supply for Northern Territories based on renewable Energy Sources Usage" has begun according to Federal Authorities decision by two Ministries - Fuel and Energy Ministry of Russian Federation and Ministry for Nationalities' Affairs and Regional Policy. This Programm - is the realization of "Energy Development Strategy of Russia", approved of the Government of Russian Federation and of the President of Russia.

The Programs' Goal. Secure by 2000 substitution of at least 1 mln. tons of liquid fuel, of long distant delivery at the expense of nonconventional renewable sources of energy and of the local fuel using.

The Programms' objects. The Extreme Norths' Regions, the territories similar to them, as well as the places of resides of small Northern tribes, situated in 31 subjects of Russia Federation, in their numbers in 15 lands and regions, in 6 republics and in 10 autonomous districts. Their power supply have to be based on gradually substitution of dear liquid fuel by nontraditional renewable power sources and by local sorts of fuel. This process have to be accompanyed with improving of power supply systems reliability and their economical efficiency. In scope - the territory involved in the Programm compose almost 70% of all-Russia territory, here include Europeen North, Siberia as a whole and Russian Far East.

Interconnection with another programms. Ministry of Nationalities of Russia has prepared for consideration in Russia' Government the State joint programm "Economical and Social Development of Russia's North". In this programm, which includes numerous problems of the North, as components enter another (for a special purpose) programms. One of these programmes is the program "Power Supply for Northern Territiries based on Renewable Energy Sources Usage" (shortly -"Power Supply for Northern Territories").

Into the joint summary programme enters also the Federal programme "Economical and Social Development of the small nationalities of North untill 2000". On the last stages of negotiations and agreement is now the special Federal programme for power supply systems' development of Russia' agricultural industry on the base of nonconventional power sources using till 1995-2000. The name of the programme - "Renewable rural power supply-2000". The programm has been worked out by the Ministry of Agricultural Products of Russia. The tasks of last programme will be taking into consideration in the programm "Power supply for Northern Territories."

Brief contents. In order to accomplish of the programms' goal it's necessary in the first approximation to put into operation of the autonomous electrical generating units in total capacity of 500MW and heat generating units in total capacity 600MW.

In the Russia' Federation Northern regions will be choosen 5-10 settlements, there the power supply systems could be provide by local renewable and traditional energy sources.

Thus the the programme will consists of 150-200 projects. As a project could be considered the large scale implementaition of small individual portable units of nonconventional energy source(wind power sets and micro-hydropower sets(HPS) with the capacities up to 1kWt, solar waterheaters for shower, solar's boilers and etc).

The programme has to include three blocks - technical, economical and organization.

In the technical block has to be the list of projects with mentioning of their location, installed capacity of the renewable and small energy generating units, customers, executors and the terms.

In the economical block it's

necessary to work out the drafts of the standard-juridical and the examples of financial documents (business-plans, technical-economical assessment, etc.) of federal and regional levels, which secure the financial support for the programme from different sources.

In organization block it's necessary to foresee the works on organizing producing,assembling and maintenance of the nonconventional and small power units at federal and local level.

General co-ordination of the works, in their numbers, the works on obtaining and on collecting set of the units, been delivering due to the grants, could be fulfilled by Federal center on small and nonconventional energy sources.

The criterions for choosen of first rates installed units. If the settlement is included into the programme, the following data have to be cleared:

1.1 The level of fuel shortage. Have to be delivered the data on satisfying the needs in fuel during 1993-1994 for the settlements.

1.2 Availability of renewable and traditional energy resources.

Have to be delivered the data on wind and sun shining hours a year, according to the data of the nearest meteorological station. The data on deposites of organic fuel.

1.3 Chacteristics of energy consumption.

Maximum of electrical power consumption (if possible, the daily loads' diagram for winter and summer months should be presented).

Discharge and kind of fuel for heating and food preparation.

In first turn in programme enters small settlements with electrical loads in limits 10-20 kW, 40-60kW, 100-200kW, 500-1000kW. Usually not excludes the settlements with the loads more, than mentioned above. Possibility to create rather large wind power stations could be consided too.

1.4 Kind of equipment which could be installed in a settlement and the conditions of it's transportation to the place. Should be present the type of equipment, type of transport and the terms of delivery to the place.

1.5 Availability of building-assembly enterprises.

1.6 Availability of the maintenance staff for units' service. The electricians are need for such service. If in settlement they have diesel-electrical generator, the former services' staff of this generator is enough for the units of nonconventional power engineering.

1.7 Customer, that is should be define the organizations, which could be customers, as well as the sources of financing.

The programmes' financing. Approximate cost of works on the programme (substitution of 1 mln.tons) been estimated in 900-1000 mln.US$., that is about 200 mln.US$ per year. Such a big money could be founded in several ways. There is no hope to the help from the federal budget, due to hard financial situation in Russia.

1. The main role in providing with investments should play the regionals' budgets. For this one offers to use means of environmental funds, the means saved due to decreaseing of fuel' discharge, means which are includes as component into tariffs for electrical and heat energy and are intended for energy complex' development.

2. The second source could be the means of international funds and programmes, been elloted for construction of some demonstration projects with participation of American, Danish, Finnish and German firms under the conditions of up to 70% discount on the equipments, delivered from these firms.

3. The third component should be obtaining of grants and credits from the World Bank under conditions - 7-8% of interest, on the period up to 15 years, with delaying of payment on 4-5 years.

4. Share participation (in proportion 50%-50%) in the demonstration objects' construction by Ministries, Russia' companies and firms, the Mimistry of Fuel and Energy of Russia, the Ministry of Nationalities, the Ministry of Agricultural Products, Ministry of Defence, the Federal Service of Frontier Guards of Russia, RSS "Gasprom", SOC"LookOil", SC"Surgutneftegas", etc.

The financing of the programmes' working out should be made by the means of Russias' Ministries of Fuel and Energy, Nationalities and Sciences. The total volume of financeing to work out the programme in 1995 is 500 mln. of roubles.

The management on the programme preparation. Head of the programme is Deputy Minister of Fuel and Energy of Russia' Federation Mr.V.Bushuev, the deputy head of the programme is Deputy

Minister of Nationalities of Russia' Federation Mr. A.Volgin, and coordinator of the programme, cheaf of the working group, is the first deputy-chief of the Board on energy-saving and nonconventional sources of energy (Ministry of Fuel and Energy) Mr. P. Bezrukikh according to common order of the Ministry of Fuel and Energy and the Ministry of Nationalities.

The main tasks for the working group are as follows:

- to fulfil analysis of energy consumption for subjects of Russia' Federation, which include territories (regions) of Extreme North;
- together with the regions make the list of projects, using nonconventional renewable sources of energy;
- to evaluate concerning each project the avaliability of the renewable and nonconventional resources of energy;
- to evaluate the needs in equipment for projects' realization and coordinate these needs preliminary with regional authorities and with manufacturers of the equipment;
- to study the conditions and mechanisms of the projects' financing, which would be build:
- for the regional expenses;
- with attraction of money from international institutions;
- with the attraction of the means from foreign firms;
- at the means of World Bank credits, after obtaining the grants;
- to propose of organizing structures for the programmes' realization management;
- to work out juridical ensuring for the programmes' realization;
- to present the programme to the Ministry of Fuel and Energy and the Ministry of Nationalities headquarters for confirmation.

To work out business-plans for the international cooperations' projects.

To joint the efforts of all institutions, which are involved into working out of feasibility study and projects' materials, as well, as of organisations, having the relations, agreed by contracts, concerning to construction of the object of small and nonconventional power-engineering in Northern regions.

<u>*Economical assessment of the wind energy using*</u>. The economical conditions in different regions of Russia are strongly diverse, and that's the reason of impossibility to make the precise universal economical calculations. Detalised economical calculations will be ful-

filled as far, as will be worked out the business-plans of individual objects. But the main milestones could be shown already now. The wind energy resources in northern Russia territory are fairly enough to ensure the using of wind-power sets' installed capacity up to 4000 hours per year, and in some region - up to 6000 hours a year.

Lets take for rough estimation the lower figure - 4000 hours a year. That's mean, the wind-power set with the installed capacity, for example of 20 kW, would produce 80 000 kWh a year. For the producing of the same quantity of energy by diesel-generator it takes about 40 tons of diesel fuel (with specific diesel-generator discharge in 0,5 kg of fuel per 1kWh). If the diesel fuel price, taking into account transportation expenses, is 1,5 mln. of roubles (320 US$) per ton, the total fuel cost is 12 800 US$. From these figures possible to define the cost of wind power set itself. It should be about 1500 US$ per 1kW of installed capacity.

Here I can mention, that Russian made wind-power sets have similar prices.

Another perspective direction of wind energy using in Northern regions is producing of heat, exactly speaking - hot water for common use and for heating. Now for the same purposes are used nonefficient small-size boilers on diesel fuel. Wind power sets for heating are rather simple - they doesn't need in supporting stability of frequency and voltage, they doesn't need in complicated automatic equipment for ensuring of parallel work with diesel generators, as a result the cost of such wind-power sets rather decreased. In addition, here appear a possibility to use wind energy in wide range of wind speeds, especially with the winds of low speed. Preliminary evaluation shows that in such a condition the repayment term could be 1,5-2 years.

That is the reason we think in this programmes' goal fulfilment (in substitution of 1 mln. tons of fuel), share of wind energy could be 50%, and the rest falls to all other kinds of renewable energy sources.

ENVIRONMENTAL EXTERNAL EFFECTS FOR WIND POWER AND COAL

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INTRODUCTION

The production of energy causes different damages to the environment depending on the energy production technology. The common term for the costs of these environmental damages are externalities. An external effect is said to exist whenever:

1. An economic activity in the form of production or consumption affects the production or utility levels of other producers and consumers.

2. The effect is unpriced or uncompensated.

This article summarises some of the results achieved in a project carried out in Denmark with the purpose to assess the environmental damages and the external costs in the production of energy. The project has especially handled renewable energy versus energy based on fossil fuels.The project has been a collaboration between the Technical University of Denmark and Risø National Laboratory. The research institutions have considered different energy production technologies in the project. The energy production technologies that have been considered by Risø National Laboratory and will be reported and compared in this paper are the following:

- Wind power
- A coal-fired condensing plant

In the project the environmental damages are thus compared, and externalities in the production of energy using renewable energy and fossil fuels are identified, estimated and monetized. The following result applies in general to the applied technologies.

Only the environmental externalities have been assessed in the project. Social and economical externalities, e.g. related to changes in implyment or depletion of resources, are not included in the project. The cost concept is based on marginal damage cost, in principle taking as starting point the level of pollution that exists today.

The methodology, which has been used in order to find and monetize the environmental externalities, consists of the different processes shown in Figure 1.

The identification step involves a description of all the processes in the production of for instance energy by wind energy, an assessment of the environmental influences, and the damages these influences cause. The processes include the total fuel and construction cycle of the specific technology.

The quantification step is a quantification of the identified influences, for instance the amount of CO_2 emission by combustion from a coal fired plant.

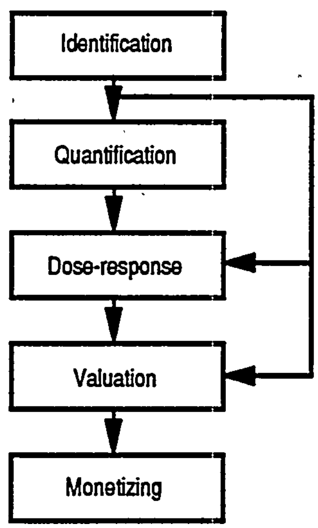

Figure 1. Methodology for monetizing externalities

The effects on the environment from the quantified influences are assessed as dose-response functions. An example of this is the assessment of how the emission of SO_2 results in acid rain, and how the damage from the acid rain affects forests in terms of lost timber.

In the valuation step the aim is to assess the monetary value of the damages, that is estimating the price of corn (yield), the price of fresh water, the price of human life etc.

All together these assessments lead to the monetizing step of the externalities. The monetizing may be expressed in the following way:

*Monetizing of the externalities = quantity * dose-response * price*

where the quantity is the quantified influence given from the quantification step, dose-response is the damage, that the quantified influence results in per unit, and the price is the price per unit of damage.

A serious problem in the assessment of the extent of the externalities is the uncertainty related to the assessment. The uncertainty is due to different conditions, the main being:

1. Insufficient knowledge to the dose-response effect.
2. The time horizon.
3. Irreversibility.

It is possible to reduce the first kind of uncertainty by more research in this area, but it is impossible to reduce the uncertainty related to time horizon. This means, that all the externalities are subjects to uncertainty, and the externalities will therefore be estimated in an interval.

WIND ENERGY

In the case of wind energy a 500 kW wind turbine and a smaller wind park of 5 MW, i.e. 10 wind turbines, have been assessed. In order to be able to compare wind power with a coalfired plant a gas turbine is introduced together with the wind turbine as a back-up technology for the wind turbine in cases without wind. The energy system wind turbine/gas turbine will in this way be able to produce electricity at any time and is therefore comparable with the coalfired plant.

The processes that have been assessed in the identification process of the energy system wind turbine/gas turbine are the following:

- Construction and establishment of the wind turbine
- Presence of the wind turbine
- Operation and maintenance of the wind turbine
- Scrapping of the wind turbine
- Construction of the gas turbine

For each process an identification of the environmental influences and a quantification of the most important influences has been carried out.

Construction and establishment of the wind turbine

The only influences identified in the construction and establishment of the wind turbine are emissions to the air due to the energy consumption in the construction phase. The most essential emissions in this process are CO_2, SO_2 and NO_x.

Presence of the wind turbine

Presence of the wind turbine will influence the nature both in a visual and recreationel way. Visually the wind turbine will influence the horizon, this may have either positive or negative effect. The experience of a walk in the nature will however be destroyed by the presence of the wind turbine. This is the recreationel effect.

Operation and maintenance of the wind turbine

The influences identified for the operation and maintenance of the wind turbine are as follows:

- Transmission of sound
- Electromagnetic radiation
- Influence on flora and fauna
- Emissions to air

The transmission of sound is an atmospheric influence caused by the operation of the wind turbine.

The electromagnetic radiation is both visual and atmospheric. The visual radiation is reflections due to the rotation of the wings, and will influence the horizon and people living nearby the wind turbine. The atmospheric radiation will influence radio and television signals to the residences close to the wind turbine.

Influence on flora and fauna is an mechanical influence due to the rotation of the blades. This may influence the life of birds nearby the wind turbine, also there may be problems if a blade is destroyed, hitting people on ground.

Emissions to the air is connected to the operation and maintenance of the wind turbine, where the production of different new components will cause emissions.

Scrapping of the wind turbine

Scrapping of the wind turbine will cause emissions to the air, especially from burning of fibre glass.

Construction of the gas turbine

The construction of the gas turbine will cause emissions to the air due to the production of different materials to the wind turbine.

Only a few of the above mentioned influences has been found relevant and important to quantify as damages related to wind energy. These influences have been quantified in Table 1.

Table 1. Quantified influences and damages for wind energy

Influences	Quantification 500 kW wind turbine	Quantification 5 MW wind park
Emissions to air (g/kWh)		
CO_2	11 - 27	11 - 27
NO_x	0.04 - 0.1	0.04 - 0.1
SO_2	0.05 - 0.13	0.05 - 0.13
Transmission of sound (residences /kWh)	$0.1 - 0.4 * 10^{-6}$	$0.05 - 0.2 * 10^{-6}$

CONVENTIONAL COALFIRED CONDENSING PLANT

The assessment of the environmental externalities in connection with energy production based on coal is related to a conventional coalfired condensing plant with an effect of 350 MW. The plant is a marginal plant equipped with a desulphurisation plant able to remove 85 % of the SO_2-emission and de-NO_x burners reducing the NO_x-emission about 70 %.

The processes which are assessed are the following:

- Construction of the plant
- Fuel cycle
- Presence and operation of the plant
- Scrapping of the plant

The fuel cycle consists of different processes as shown in Figure 2. As seen from the figure there is no national transportation in Denmark. The reason for this is, that the coal is transported by ship directly to storage in the harbor in the area of the coalfired plant.

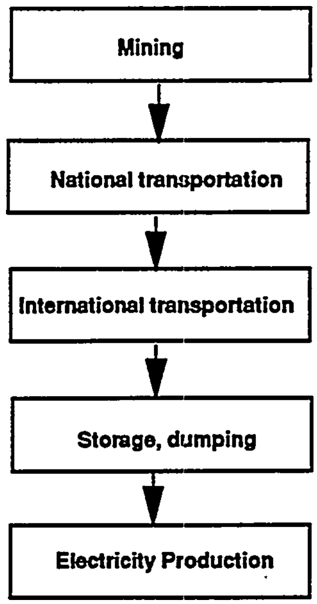

Figure 2. The fuel cycle

Each process has been assessed in regard to environmental influences and damages. The influences identified for all the processes are as follows:

- Emissions to the air
- Emissions to the ground
- Emissions to the sea
- Transmission of sound
- Influence on flora and fauna
- Influence on nature experience
- Influence on traffic

Emissions to the air will occur in all the processes due to production of materials, coal emissions from the mining, transportation of coal by ship, storage of coal and due to electricity production.

Emissions to the ground is an influence caused by the electricity production process, where fly ash is stored.

Emissions to the sea will occur during transportation of the coal by ship, where oil leaks from the ship may appear.

Transmission of sound will occur in many processes. During the mining there will be machinery noise, during transportation there will be noise from railways and by coal loading, and also in the electricity production process and the operation of the plant there will be transmission of sound.

Influence on flora and fauna is caused by the presence of the mine, but also during the electricity production process there will be influence on flora and fauna due to the desulphurisation process, where large amounts of chalk will be excavated. Also the presence of the plant will influence the nature in the area.

Influence on nature experience is also caused by the presence of the mine and by the presence of the plant.

The transportation of coal by railway and by vehicles will affect the traffic, but also transportation to the plant during operation will influence the traffic.

The most important of the above mentioned influences have been quantified as shown in Table 2.

Table 2. Quantified influences and damages for coal

Influences	Quantification 350 MW coal plant
Emissions to air (g/kWh) • CO_2 equivalents • NO_x • SO_2 • Particles • VOC • NMVOC	 875 - 1018 1.5 - 2.0 1.5 - 1.9 0.17 - 0.19 0.02 - 0.03 0.04 - 0.06
Transmission of sound / influence on flora and fauna (residences /kWh)	$2 - 7 * 10^{-9}$

MONETIZING EXTERNALITIES

The monetizing of the externalities is carried out based on the quantification process, the dose-response process and the valuation of the damages. An example of the monetizing is shown in Table 3.

Table 3. Example of monetizing externalities

Monetized externality	Influence	Dose-response	Value
Costs of loss in fresh water	= CO_2 (ton/GWh)	* Loss in fresh water (m^3/ton CO_2)	* Price of fresh water ($/$m^3$)

The external effects are assessed and split into three geographical areas:

- Local, which is damage occurring within a vicinity of 50 km from the plant.
- Regional, relating to any damage occurring within a radius of 3000 km from the plant.
- Global, concerning any damage attributed to greenhouse gasses.

There is a considerable difference in the way that the local and regional externalities, and the global externalities are assessed. This applies to both the methodological way and uncertainty about the available data. The local and regional externalities have only an effect on a very short term, where both emissions and damages are known with a reasonably certainty. Regarding the global externalities the emissions are well known, but the extent of the damages are based on long term scenarios for the development of the concentration of CO_2-emissions in the atmosphere, and the raise in temperature this will cause. The values associated with the damages are very uncertain as well, due to the long term scenario.

Because of this the total monetizing process is divided into two categories: local and regional externalities, and global externalities.

Monetizing local and regional externalities

The quantified local and regional influences are shown in Table 4.

Table 4. Quantified local and regional influences

Influences	Wind Power	Coal fired plant
Local Emissions to air (g/kWh) • Particles Influence on residences/ kWh	 - $0.1 - 0.4 * 10^{-6}$	 0.17 - 0.19 $1.9 - 7.4 * 10^{-9}$
Regional Emissions to air (g/kWh) • SO_2 • NO_x • NMVOC	 0.05 - 0.13 0.04 - 0.10 -	 1.5 - 1.9 1.5 - 2.0 0.04 - 0.06

A part of the regional emissions from the coal fired plant is international, for instance the emissions related to mining and the international transportation of coal. About 35 % of the SO_2 emission from coal and 55 % of NO_x are international emissions, while the emission of particles is national. 0.5 g SO_2/kWh and 0.6 g NO_x/kWh of the emissions from the coalfired plant are emitted at sea, and these emissions will therefore have no regional consequences in terms of acid rain.

For the wind power especially the influence of noise on nearby residences is important. The estimate of influence on residences in general is rather uncertain with a variation on a factor four from the low to the high estimate.

The connection between influence and damage (dose-response) is shown for the local and regional externalities in Table 5.

Table 5. Dose-response for local and regional externalities

Consequences	Influence	Dose-response
Local Health effects • Illness Death	 Particles Particles	 1.9-6.7 days/ton 0.7-1.8 $*10^{-4}$ dead/ton
Regional Loss in forestry Loss in agriculture Health damages • Stay in hospital Loss of working days	 SO_2, NO_x SO_2 Particles	 0.4-1.6 ton biomass/ton 0.15-0.6 ton biomass/ton 0.05-0.2 stays/ton 11.3-40.0 days/ton

Most of the dose-response estimates are based on studies carried out for the European Commission. In general a considerable variation is found in the dose-response estimates, often a factor 3-4 between low and high estimate. The reason for this variation is mostly that the categories are very inhomogenous and therefore have a considerably variation.

Table 6 shows the costs related to the local and regional consequences. In general, the estimates are based on market prices. Some of the estimates are uncertain. For instance the damages on buildings and monuments differs with a factor 7 from low to high estimate.

Table 6. Costs of local and regional consequences

Consequences	Price
Health effects	
• Illness (loss of working days)	125 - 190 $/day
• Stays in hospital	435 - 715 $/day
• Death	0.5 - 0.9 mill. $/life
Loss in fresh water	0.25 - 0.7 $/m^3
Loss in agriculture	185 - 235 $/ton yield
Loss in forestry	65 - 110 $/ton tree
Damages on buildings / monuments	235 - 1670 $/ton SO_2
Visual, recreational, noise damages	40 - 115 $/kWh/year

Altogether the local and regional monetized externalities for wind power and coal are as follows:

- Wind power: 0.02 - 0.15 ¢/kWh
- Coal: 0.08 - 0.67 ¢/kWh

The estimated local and regional externalities are found to be moderate.The main reason for this is, that the analysis is performed for new highly developed energy technologies on a high developed level. If the coal fired plant analyzed was an average plant instead of an advanced coal fired plant the regional pollution would be doubled.

Monetizing global externalities

The global emissions, which have been quantified are CO_2, CH_4, CO and N_2O. These emissions have been converted to CO_2 equivalents by means of Global Warming Potential factors (GWP):

- Wind power: 11 - 27 g CO_2 equivalents /kWh
- Coal: 875 - 1018 g CO_2 equivalents /kWh

The emission of greenhouse gasses is considerable for the coal fired condensing plant, while the emission of greenhouse gasses in the wind power case is limited to the emission related to the construction of the wind turbine. Regarding the coal fired condensing plant about 10% of the global emissions are international emissions.

The dose-response for the global emissions is shown in Table 7 both for the year 2045 and for a yearly average until year 2045. The year 2045 is representing a time horizon of approximately 50 years, equivalent to a doubling of the concentration of CO_2 in the atmosphere (the case normally assessed in analysis of this type). The estimates are based on the damages in year 2045, and the average have been calculated on the assumption of a linear connection between the CO_2 concentration, increase in temperature and the damage hereby. This crude assumption tends to overestimate the average yearly damage, if the actual damage function between CO_2 concentration and damage is exponential.

Table 7. Dose-response for global emissions

Consequences	Year average (damage/Gton CO_2)	Year 2045 (damage/Gton CO_2)
Increased mortality, dead	2,500-10,000	5,500-22,000
Loss in fresh water, m^3	$0.1\text{-}1.2 * 10^{10}$	$0.3\text{-}2.7 * 10^{10}$
Loss in agriculture, ton yield	$0.4\text{-}1.7 * 10^{6}$	$0.9\text{-}3.8 * 10^{6}$
Loss in sealand, km^2	40-100	80-230
Loss in mainland, km^2	20-50	40-120

The costs per unit of the global consequences are shown in Table 8. Some of the consequences, listed in Table 8, are not evaluated using dose-response functions, but monetized directly in relation to the influence (emission).

Table 8. Costs of global consequences year 2045 (1993 prices)

Consequences	Price, year 2045 (1993 prices)
Increased mortality	0.2-0.7 mill. $/life
Loss in agriculture	135-335 $/ton yield
Loss in forestry	0.08-0.15 * 10^3 mill. $/Gton CO_2
Loss in biodiversity	0.2-1.35 * 10^3 mill. $/Gton CO_2
Coast protection	0.02-0.20 * 10^3 mill. $/Gton CO_2
Loss in sealand	1.35-3.85 mill. $/km^2$
Loss in mainland	1.35-3.85 mill. $/km^2$
Room heating / cooling	0.2-0.8 * 10^3 mill. $/Gton CO_2
Tourism	0-0.4 * 10^3 mill. $/Gton CO_2
Loss in fresh water	0.25-0.65 $/m^3$

The global monetized externalities for the year 2045 are as follows:

- Wind power: 0 - 0.1 ¢/kWh
- Coal: 0.25 - 4.10 ¢/kWh

The largest part of the monetized global externalities is related to an increase in mortality because of climate change. Loss in fresh water also constitutes a considerably part of the global externalities.

Coal-fired power plants have a large monetized value for the global externalities, while those related to wind power can almost be neglected.

It must be stressed, that uncertainties related to the evaluation of the global externalities are very high, and that only those types of damage, that can be identified today, are included. Without doubt, a number of future externalities, not accounted for in the study, will most likely arise. For that reason, the monetized global externalities in this study most probably will account only for a subset of total externalities related to the greenhouse effect.

CONCLUSION

The main results of the assessment of the external costs for the two energy production technologies, wind power and coal fired condensing plant, are given in Table 9.

The estimates are yearly estimates in average in a period of 50 years (year 1995 - 2045), and the numbers differ therefore from the above mentioned global and local/regional externalities, where the global externalities are for the year 2045. The assumptions are based on IPCC estimates for a doubling of the concentration of CO_2 in the atmosphere.

Table 9. Total external costs for wind and coal

Energy Production Technologies	Estimated External Costs yearly average
Coal	0.2 - 2.6 ¢/kWh
Wind	0.02 - 0.2 ¢/kWh

As there are large uncertainties attached to the figures both a high and a low estimate have been estimated.

Concerning the local/regional externalities the following was found:

- The most important monetized values are attached to damage on buildings and monuments (acid rain) and influences on residentces (noise, visual impact).
- In general, the monetized externalities are moderate, mainly due to the use of new, highly efficient technologies in the analysis.

Regarding the global externalities the following was found:

- The most important monetized externalities are increased mortality and loss of fresh water
- Evaluating global externalities today is highly uncertain. The monetized global externalities can be expected to constitute only a subset of the total existing and future global externalities.

By far the largest external costs are related to the emission of greenhouse gasses, especially CO_2, accounting for more than half of the total damages. This is due to the large economic consequences of the rise in temperature related to the greenhouse gasses, e.g. rising sea level, reduced yield, increasing morbidity etc. The effects of local and regional pollution as for instance acid rain play a smaller role. This fact points in the direction of further research into the relationship between rising CO_2 concentration, temperature and economic consequences.

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VALUE OF ENERGY FROM THE WIND

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World-wide, several studies considering the value of wind energy have been undertaken. The variety of values estimated, pinpoints that the value of wind energy is not a fixed number, though depending on the local conditions.

This paper firstly lists and discusses the aspects that should be considered while assessing the value of wind energy. These aspects include lifetime assessment of

- fuel savings while taking account for possible utility system operating penalties,
- power generating capacity savings as introducing wind energy may reduce other capacity investments still maintaining the loss of load expectation level and an adequate mix between peak and base load units, and
- savings connected to emissions.

Secondly, the value of wind energy is assessed for different utility systems and wind energy penetration levels. The study indicates the value for a range of wind energy penetrations and utility systems, i.e. utility systems based on a) hydro, b) nuclear, c) coal and d) diesel fuel.

The value of wind energy in terms of fuel and capacity savings may be quantified using more or less standard power system simulation tools. Regarding the savings connected to the emissions, it is now generally recognized, that external costs from energy production can constitute an essential part of the total costs. Using the concept of damage cost, the externalizes in relation to the electricity production for different power generation technologies are discussed and quantified. Further, these costs are compared to the abatement costs on power plants.

Financial incentives have been and are used for stimulating the market for wind power. Partly, incentives are used for buying down the price of new technology to a cost competitive level expected to be reached in the future, and partly incentives are used for filling the gap between a low selling price and a true expected higher value of wind energy. Certainly, there is a link between incentives and the value of wind energy, and the paper concludes by assessing different national incentive models and comparing these with relevant wind energy cost and value estimates.

Technical and Economical Aspects of Wind Energy Applications in Germany

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ABSTRACT: The use of renewable energy for the continuously growing global population is becoming increasingly important. These forms of energy not only broaden the urgently needed resource base, but are also free from emission of CO_2, SO_2, NO_X etc. The Federal German Government early recognized this and has provided more than DEM 4000 million for this purpose since 1973. Together with Japan and the USA, Germany belongs to the three leading nations in the world in R&D on the application of renewable energy. It has by far the largest and most broadly based programme in Europe. The technical and economical progress of wind power is very promising in Germany. It has been extensively stimulated by continuous governmental support of R&D and since 1989 by the large scale demonstration programme „250 MW Wind". Since 1991 another important impetus has been the „Electricity Feed Law" which regulates incentives for power produced from renewable energy sources (wind power presently 0.1728 DEM/kWh). In 1994, the rated wind power capacity was doubled to 643 MW. Electricity production in 1994 was around 1000 million kWh or 0.2% of total German electricity production. The often discussed goal of producing one or more per cent of the German electricity by wind power seems to be attainable on a medium time scale by modern medium scale wind turbines or even large scale turbines. This is based on the promise that various nontechnical barriers will be overcome.

1 INTRODUCTION

The use of wind energy in the Federal Republic of Germany has made enormous progress in the years since 1990, significantly supported by funding programmes of the federal and state governments, especially by the "250 MW Wind"-Programme of the Federal Ministry for Education, Science, Research and Technology BMBF. This development has been decisively influenced by the adoption of the so called "Electricity Feed Law" (EFL) of December 1990. This regulates the input and payment of electricity from renewable energies (e.g. wind, solar, water) by the utilities. The payment for electricity from wind power amounts to 90 % of the average proceeds per kilowatt hour of electricity delivered by the utilities to the final consumer. This corresponds to 0.1728 DEM/kWh for the year 1995.

2 DEVELOPMENT IN GERMANY

The increase of wind energy utilization in Germany is reflected in several aspects. Favourable boundary conditions, for example, have not only influenced the installation rate of new wind energy converters (WECs), but have also improved plant engineering. Fig. 1 illustrates that the growth of the WEC installation rate is strongly influenced by the "250 MW Wind"-Programme. Note that the upper part of the column in Fig. 1 includes many wind farms which were only built by BMBF's support for a fraction of the WECs in the farm.

Since 1989, all WECs supported under the "250 MW Wind"-Programme have been accompanied in running operation by the Scientific Measuring and

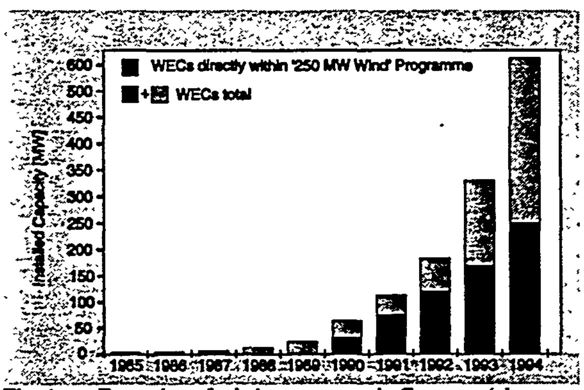

Fig. 1. Expansion of wind energy uses in Germany (plants interconnected with the grid)

Evaluation Programme (WMEP). By 30.06.1995, more than 1400 WECs with approx. 290 MW installed rated power were incorporated in the measurement programme carried out by the Institut für Solare Energieversorgungstechnik (ISET) on behalf of the BMBF. Since the programme's power of 250 MW is related to WECs power at 10 m/s wind speed, there is still 20 % of the support quota available for 1995. One third of the new plants included in the course of 1994 again have an increased rated power of more than 500 kW compared to previous years. This has increased the average WEC capacity within WMEP to nearly 200 kW.

The evaluation of the operator reports on electricity production by WECs under the "250 MW Wind"-Programme shows a total annual energy yield of 460 GWh for 1994. This corresponds to an increase of more than 50 % in electricity production from wind power compared to the preceding year (303 GWh). In the federal state of Schleswig Holstein alone, more than 200 GWh were produced by WECs funded by the Federal Government, followed by the state of Lower Saxony with approx. 150 GWh and Mecklenburg Western Pomerania with roughly 45 GWh. If the annual yields from WECs are classified in site categories, the following breakdown is obtained: roughly 345 GWh (75 %) were produced at coastal sites, 72 GWh (16 %) at inland sites and 40 GWh (9 %) at sites in the low mountain range. The total electricity production from wind energy of all WECs in Germany, including the installations not supported by the 250 MW Programme, should be in the range of 1000 GWh for 1994, with 485 GWh reported alone by the state of Schleswig Holstein.

The improved WECs technology is demonstrated by the current availabilities of 98 to 99 per cent achieved by the commercial WEC types in different regions. If it will be possible to transfer this documented WEC reliability to the next generation of larger WECs, a considerable increase in specific annual energy yields is to be expected with correspondingly greater hub heights and further efficiency improvements (see Fig. 2). Nevertheless it is supposed that current specific production costs will be maintained, not least due to improved manufacturing processes.

3 COSTS AND ECONOMICS

The economics of a WEC project depends essentially on the operator-specific boundary conditions. In particular, a distinction must be made with respect to the calculation basis between utilities producing electricity themselves and utilities without electricity production as well as between private persons and operator communities.

A simplified approach is used to determine the electricity production costs in DEM per produced kilowatt hour for the investor group of private persons and operator communities. This approach includes the following costs:

- investment costs: WEC costs, extras, foundation, grid connection, planning, licensing etc.,
- operating and maintenance coasts: repairs, insurances, monitoring, management etc. ...
- capital costs: interest and repayment of the loan,

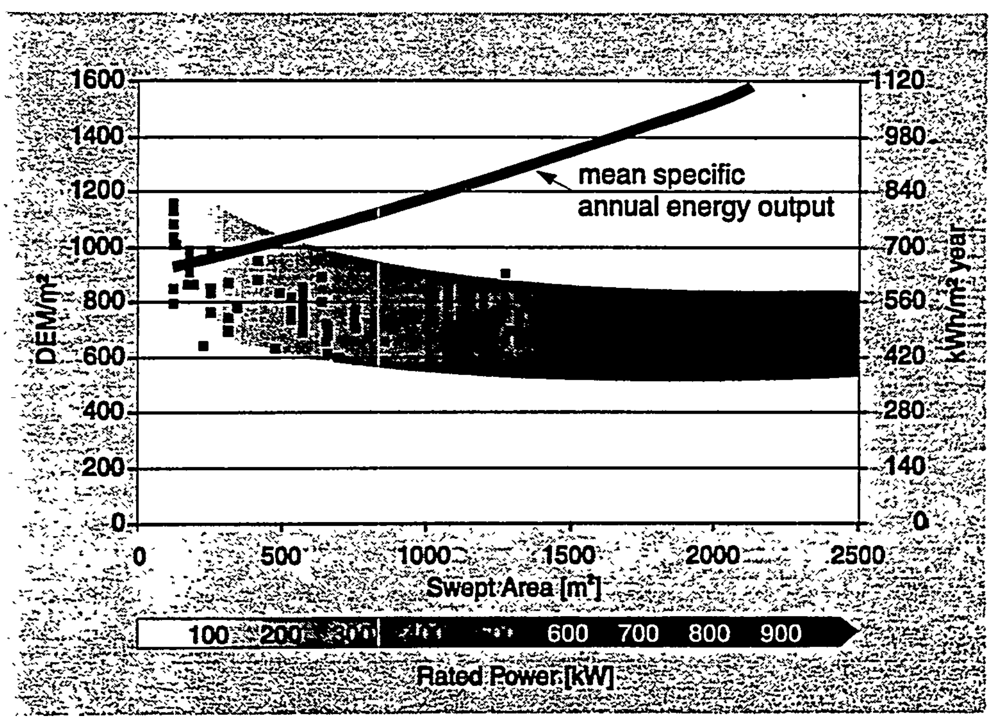

Fig.2. Specific plant costs and annual energy

The by far largest portion of wind power installed in Germany is financed by special low interest loans for environmental protection measures. The Federal Ministry of Economics grants long term, reduced-interest loans at about 1 % below the current interest rate for the financing of environmentally relevant measures, such as wind power installations, via the Deutsche Ausgleichsbank/DtA. The payout rate for the loans depends on the percentage of the loan in the total investment and may amount up to 100 %. The first two years are redemption free and the interest is fixed for the total loan period. In June 1995, the interest rate for credits under the DtA Environmental Programme was 6.50 % in West Germany and 6.0 % in East Germany. The credit period is generally ten years.

The volume of support for wind power plants by loans of the DtA has continuously increased in recent years. The types and volume of loans in the years 1992 to 1994 are compiled in Table I [1].

The depreciation time has an essential effect on the electricity production costs. Taking into account the present status of wind energy technology with no long-term experience and a further rapid development of this technology we choose 10 years as depreciation time and not 20 as in most other calculations. Considerable efforts are required to determine the extras of investment and the operating costs of wind energy projects in order to obtain reliable figures. Table II shows the extras of the investment determined by a survey among several hundred WEC operators in the WMEP. They amount to 34.5 per cent of the WEC purchase price on average, which also includes transport, assembly and commissioning. The maximum value specified for the individual cost types represents upper limit in 90 per cent of all cases.

The average WEC O&M costs determined in the WMEP are in the range of 2.5 % of the WEC costs for installations with an operating time of more than two years. For a ten year WEC financing period this gives an estimated mean value of approx. 3.0 % for the third to tenth operating year based on an annual increase rate of 5 % p.a. for the O&M costs. In the first two years of WEC operation, only marginal O&M costs are generally incurred owing to warranty.

Including the cost categories specified and using dynamic calculation methods [2] electricity production costs (in DEM per kilowatt hour) are obtained for electricity production from wind energy, which decisively depend on the specific costs (DEM/kW) of the plant types (or WEC size category) installed [3]. The following boundary conditions are predefined in calculating the electricity production costs in Fig. 3 according to the annuity method:

TABLE I
WEC FUNDING BY THE DEUTSCHE AUSGLEICHSBANK DtA (values in Million DEM)

Loan Programme	1992	1993	1994
ERP Energy Conservation Programme	66,2	213,9	439,0
DtA Environment Programme	35,9	89,5	172,3
municipal loan programme	15,3	-	-
total	117,4	303,4	611,3

TABLE II
EXTRAS OF INVESTMENT COSTS ACCORDING TO AN OPERATOR SURVEY

Type	Average [%]	Maximum [%]
grid connection	8,7	18,0
foundation	9,1	15,0
internal cabling	5,3	11,0
planning	1,5	2,9
building permission	3,4	8,0
infrastructure	2,0	4,1
site purchase	2,7	5,7
other extras	1,8	3,8

- depreciation time: 10 years
- financing fraction: 100 %
- support fraction: 0 %
- interest rate (mixed calculation): 7.5 %
- extras of investment: 33 %
- average O&M costs: 3 %

The nominal annual energy yield of the WECs under consideration is calculated from measured characteristics and in each case relates to a reference site with an annual mean wind speed of 6.0 m/s at 30 m height above ground (roughness length z_0 = 0.05 m) assuming a Rayleigh distribution. The nominal energy yield of the WECs considered is specified to be about 0.29 GWh (150 kW), 0.58 GWh (300 kW) and 1.25 GWh for the 600 kW plant [3].

The calculated electricity production costs for plants of the 150 kW category as well as for 300 kW and 600 kW installations are plotted over the reference variable "annual energy yield" (Fig. 3). The result is that the electricity production costs are clearly more favourable for larger plant types. Furthermore, larger plant types also exhibit greater stability with respect to fluctuations of the annual electricity production costs in the case of negative deviations from the nominal annual energy yield. Thus, for example, the electricity production costs of WECs in the 600 kW power category increase by approx. 0,02 DEM/kWh in the case of a 10 % negative deviation from the nominal annual energy yield (1.25 GWh). For WECs in the power category of 150 kW the variation in electricity production costs amounts to approx. 0,03 DEM/kWh for the same fluctuation width. The electricity production costs at nominal annual energy yield are thus 0.2784 DEM/kWh (150 kW), 0.2088 DEM/kWh (300 kW) and 0.1830 DEM/kWh for 600 kW plants.

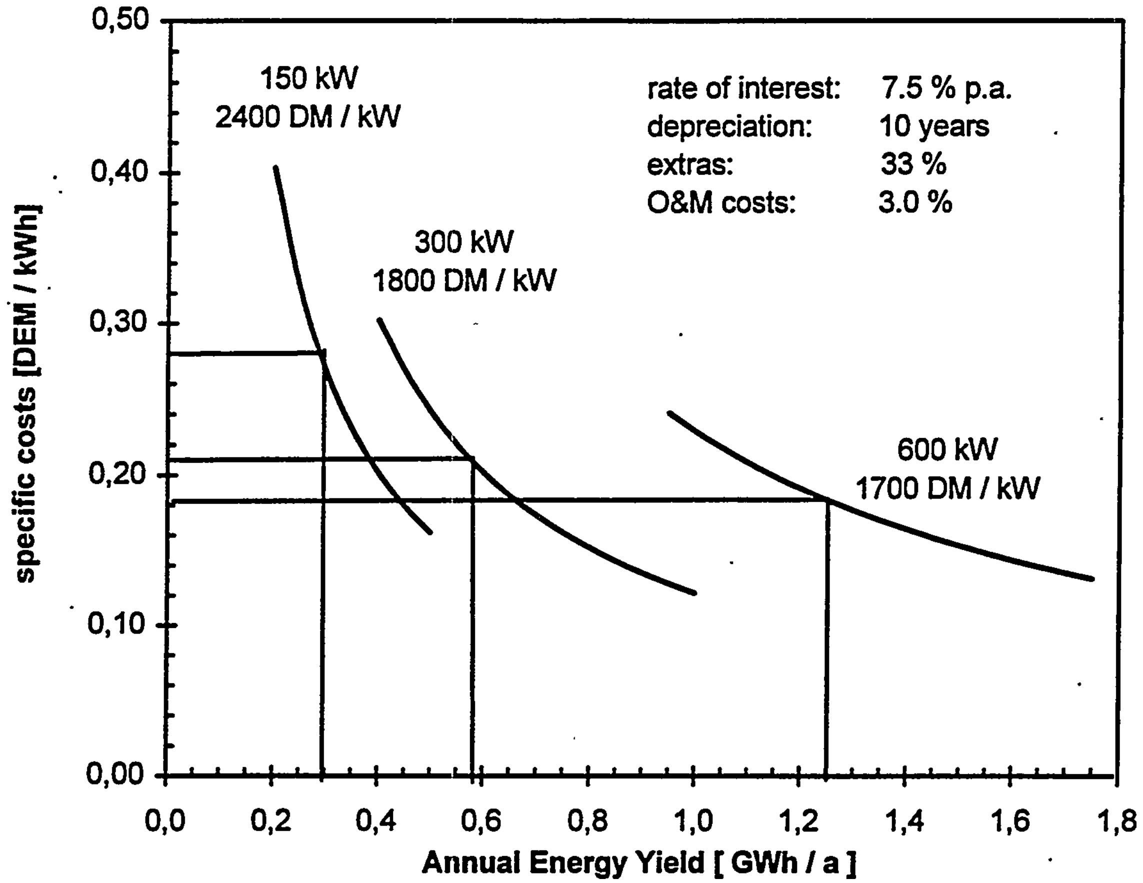

Fig. 3. Electricity production costs for different WEC power categories

Further hints for the economics of the considered WECs are gained by a comparison of the calculated annual costs and the necessary or recorded earnings by selling wind power. The annual costs were calculated with the chosen parameters as approx. DEM 228000 for the example of a 600 kW WEC. They are composed of the costs of financing the capital from outside sources of about 198000 DEM/a and the costs for operation and maintenance of about 30000 DEM/a. At the present rate of payment for electricity fed into the grid (1995: 0.1728 DEM/kWh) an annual energy yield of approx. 1.30 GWh/a is required for financing the WEC for a period of 10 years.

If the annual energy yield is related to the WEC rated power, the usual electricity quantity of "full load hours" is obtained. Our example of a 600 kW WEC requires about 2200 full load hours per year for the return on investment within a period of 10 years. The 300 kW WEC would require 2300 h. In general these full load hours are only achieved by WECs at or near the German coast where the annual average wind speed at 10 m above ground is between 5.5 and 6.5 m/s. In the calmer coastal hinterland (inland category) as well as in the low mountain regions, the full load hours so far determined are clearly below these values.

With the result of our data analysis we are able to determine the full load hours in the different site categories see Fig. 4 and Table III. Basis of the evaluation are 1016 WECs which were more than 350 days in operation by Dec 31, 1994. Therefore this statistics is based on WECs of the 300 kW class. Only a few WECs of the new 500 kW class are recorded, as they were built later. About 50 % of these WECs operate at coastal sites, 35 % at inland sites and 15 % in low mountain regions. The results show that roughly 85 % of the WECs at coastal sites achieve more than 2000 full load hours, whereas only

TABLE III
DISTRIBUTION OF FULL LOAD HOURS FOR DIFFERENT SITE CATEGORIES

Full load hours	Coast	Inland	Low mountains
up to 500	0,2%	2,2%	6,6%
up to 1000	0,2%	16,0%	19,9%
up to 1500	2,6%	38,9%	32,5%
up to 2000	12,2%	30,0%	30,1%
up to 2500	37,3%	10,4%	10,2%
up to 3000	33,4%	2,5%	0,6%
up to 3500	12,2%	0,0%	0,0%
more than 3500	1,8%	0,0%	0,0%
total	100,0%	100,0%	100,0%

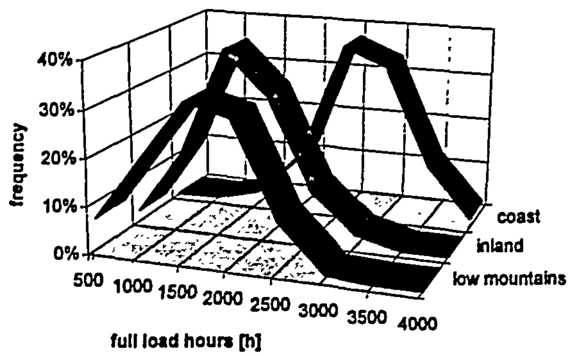

Fig. 4. Distribution of full load hours for different wind regions in Germany. Note that the figure is mathematically not exact since discrete values are shown as quasi-continuous bands

approx. 13 to 11 % of the facilities installed at inland and low mountain sites reach more than 2000 full load hours. In terms of our model calculation above this means that only about these percentages of WECs would be financed in 10 years with the income of the sale of electricity alone. This means also, that many WEC projects especially at calmer inland and low mountain sites depend on additional funding. Our evaluation should show tendencies. Strictly speaking each WEC project needs an own calculation with an individual set of parameters, finally including the individual taxes of the investor.

4 CONCLUSION AND OUTLOOK

Favourable boundary conditions such as funding by the federal and state governments, the EFL, as well as favourable loan interest rates on the capital market have caused a boom in the use of wind energy in recent years in Germany. The further development of plant technology with constant and, in part, even decreasing specific investment costs already permits economically efficient WEC operation at sites with favourable wind conditions even without governmental funding. At inland and low mountain sites, however, the WEC operators are currently dependent on investive and/or earnings-linked funding.

The use of wind power also involves relevant labour market policy aspects in addition to its positive environmental effects. At present, approx. 5000 workplaces are secured in Germany due to wind energy utilization. The company structure - predominantly small and medium-sized enterprises - has proved extremely efficient. These companies have the flexibility required to take up and continue important trends. A continuous expansion of wind power, i.e. continuity on the market and in research and development, will be necessary for a stable further development of this innovation oriented structure. This perspective is not limited by the wind potential, but quite essentially by the political will to increasingly use renewable energy sources and by a sufficient acceptance of our population in the future.

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Estimation of the external cost of energy production based on fossil fuels in Finland and a comparison with estimates of external costs of wind power

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ABSTRACT: Ekono Energy Ltd. and Soil and Water Ltd. participated in 1993 - 1994 in the SIHTI 2 research programme of the Ministry of Trade and Industry by carrying out the project "Estimation of the external cost of energy production in Finland". The aim of the survey was to assess the external costs of Finnish energy production, which are incurred by the environmental impacts of emissions during the life cycles of fossil fuels. To this end, the survey studied the environmental impacts of emissions on a local level (population centres), on a national level (Finland) and on a global level. The main target was to develop a method for calculating the economic value of these impacts. The method was applied to the emissions in 1990. During the survey, the main emphasis was put on developing and applying indirect valuation methods. An indirect method proceeds through dose-response functions. The dose-response function links a certain emission quantity, concentration or deposition to the extent or intensity of the effect. When quantitative data on hazards is available, it is possible to carry out monetary valuation by means of market prices or people's otherwise expressed willingness to pay (WTP). Monetary valuation includes many uncertainty factors, of which the most significant with regard to this study are the transferability of dose-response functions and willingness-to-pay values from different kinds of conditions, additivity of damage values, uncertainty factors and problems related to discounting.

The external cost estimates obtained partly result from calculation examples. Even though they contain great uncertainty, from them it is possible to assume the order of magnitude of hazards and what effects and components are potentially significant. On the basis of the calculations made, the damage per energy content (damage in Finland and abroad) caused by emissions from the coal fuel cycle (possible range 50 - 60 FIM/MWh$_{fuel}$) seem to be biggest of those fuel chains included in the study followed by the wood fuel cycle (40 - 50 FIM/MWh$_{fuel}$), the damage of which probably is overestimated, however. Damage caused by emissions from the heavy fuel oil cycle seem to be following in size (30 - 40 FIM/MWh$_{fuel}$), while damage of the light fuel oil and peat fuel cycle emissions seem to be smaller and of the same magnitude (20 - 30 FIM/MWh$_{fuel}$). The damage per energy content caused by emissions from the natural gas cycle are clearly smaller (< 10 FIM/MWh$_{fuel}$) than any of the above.

The external cost of wind power production in Finland has not been estimated to date. Foreign studies however suggest, that the external costs for wind power are only a few percent of those for fossil fuels and in the order of magnitude a couple of FIM/MWh$_e$.

Since the damage caused by energy fuel cycle emissions are most obviously significant as valued in money and an significant factor affecting the competitivity of different electricity production technologies, it is justified to continue their research and assessment. Results and valuation methods should be checked along with more accurate research results and changing emission levels.

1. INTRODUCTION

Energy production has several external effects, the costs of which are not included in the market price of energy, but are paid by society. For that reason, these costs are often called social costs. Such external effects include harmful health and biological effects caused by flue gases.

Since external costs are not included in the production costs of energy, they are not taken into account when comparing the social profitability or business economics of different production forms and individual power production projects. Omitting external costs is therefore, in fact, an advantage given to some production form causing externalities. However, it is also possible to make the polluter pay for any external effects. For example, the polluter has to invest in environmental technology or take out insurance policies for possible accidents, in which case the external effects are transferred to pricing and further through the marketing mechanism to future investment decisions and other energy policy choices. Before we can use the estimated external costs as a basis for internalizing the environmental impacts of energy production, all methods and calculations have to be sufficiently accurate. In Finland, energy planning still lacks methods to estimate external costs in money. Correspondingly, it has not been possible to calculate the monetary environmental benefit contributed by emission reduction measures.

2. STUDIES MADE

Environmental economics including monetary valuation of environmental effects is now the focus of vigorous research in Europe and in the United States in particular, where the valuation of environmental effects is carried out to an increasing extent as part of the cost-benefit analysis of large-scale projects or to assess the value of environmental damage caused by accidents. Examples are the Toxic Substances Control Act and part of the Clean Air Act, which both require that benefits and losses should be compared when setting new standards. One example of the last mentioned is the assessment of the damage caused by the oil tanker Exxon Valdez. "Executive Order 12291" signed in 1981 requires that cost-benefit analysis should be performed for any major projects (defined to have annual costs in excess of USD 100 million). In Europe the valuation of environmental commodities and changes in the environment has proceeded farthest in Germany and the Nordic countries. All the Nordic institutions in charge of road planning have developed methods for pricing road traffic fuel emissions and noise.

The most significant project in studying the external costs of fuel cycles is the parallel study [1], [2] carried out for the DG XII of the Commission of the European Community and the US Department of Energy. These projects investigate the harmful effects and economics of different fuel cycles. Other notable reports dealing with valuation of the environmental effects of fuel cycles are, for example, [3] - [8]. Generally speaking, this field is in a development phase in which valuation principles and methods are being developed and their applicability is being studied.

In 1993-1994, Ekono Energy Ltd and Soil and Water Ltd participated in the project "Estimation of the external costs of energy production in Finland" [9], which is part of the SIHTI 2 research programme of the Ministry of Trade and Industry (today the programme is being conducted by Finland's Technology Development Centre, TEKES). The methods, results and conclusions of this work will be presented in this paper, which also includes some specifications and amendments to the calculation examples of the SIHTI report.

3. ESTIMATION OF THE EXTERNAL COSTS OF ENERGY PRODUCTION IN FINLAND (Project of Soil and Water Ltd & Ekono Energy Ltd in the SIHTI 2 research programme)

3.1 OBJECTIVES

The objective of the above mentioned SIHTI project was to clarify Finnish energy production's external costs incurred by emission-caused environmental effects. To this end, air emissions of fuels used in energy production were studied starting from fuel production and ending at the use of fuels at energy production plants. Further, their effects on people and the environment were assessed locally (population centres), nationally (Finland) and globally. The main objective was to develop a method for calculating the economic value of environmental effects. The method developed was applied to assessing the emissions from energy production of 1990.

The report described a way of estimating the costs caused by environmental effects. This gives guidelines of how high these costs are when compared with emission reduction costs, how environmental taxes could be developed and which would be the most significant effects worth studying and worth setting limits for. The calculations made are examples and only guiding.

During the project mainly indirect valuation methods were developed and applied. Indirect methods proceed through dose-response functions, whereas direct methods value the environmental impact directly based on people's behaviour or their otherwise expressed willingness to pay. The dose-response function links a certain emission amount, concentration or deposition to the extent or intensity of the effect. When quantitative data on effects is available, it is possible to carry out valuation, for instance, by means of market prices or people's willingness to pay (WTP) or people's willingness to accept (WTA).

3.2 VALUATION METHODS USED

Valuation in the SIHTI project proceeds mainly in the following way:

- Finland is divided into the urban area (population centres) and the rural area. The urban effects to be studied are damage to materials and health effects. The rural effects (ecological effects) are damage to forests and cultivated plants.
- The measurements made earlier in population centres and at background stations are used to assess the concentrations of the (critical) emission components in population centres (averages) and depositions in the countryside. Research reports in this field are studied to find connections between concentrations (or depositions) and environmental effects.
- Global effects are the greenhouse effect and thinning of the ozone layer. These impacts are valued based on the data presented in literature.
- As soon as the damages have been quantified, market prices are used as far as possible to indicate environmental effects in money. Values based on the willingness-to-pay can also be used (eg value of a statistical life).
- The unit damage values (FIM/kg) of emission components arrived at by means of the effects in Finland are used as a starting point to estimate the damage caused by emissions emerged abroad at the beginning of the fuel cycles and to Finnish energy production emissions dispersed abroad.
- By estimating the proportion of energy production emissions among total concentrations and depositions and by using Ekono Energy's fuel chain emission calculations and the energy statistics of the Central Statistical Office of Finland, it is possible to express the damage per energy content of a fuel in the form of FIM/MWh_{fuel}.

4. RESULTS OF THE SIHTI PROJECT AND ASSESSMENT OF THEIR RELIABILITY

4.1 RESULTS

The following table (Table I) shows a summary of the estimated damage caused by emissions from Finnish energy production and greenhouse gases globally calculated during the SIHTI project. The table also contains the damage abroad caused by emissions from energy production. The latter has been assessed by applying half of the estimated average unit damage value of emission components in Finland (except greenhouse gas emissions because they are already taken into account in the global effects). Half of the unit damage calculated in Finland has been used as a calculation basis because the effects of population centres are emphasized in Finland, whereas the proportion which goes abroad ends partly in the ocean and mostly outside population centres. The assessment of the damage emerging abroad contains considerable uncertainty, eg due to the uncertainty of the applicable unit value.

TABLE I

Damage in population centres, rural areas and globally and damage abroad caused by energy production emissions, FIM million/a (1990)

		CO_2	CH_4	N_2O	SO_2	CO	NO_x	Metals	HC	PM_{10}	Σ
Health and material effects	a b	-	-	-	50 870	-	2[c] 170	4	20[d]	1670[e] 690	1740
Ecological effects		-	-	-	40	-	100[f]	-	10[f]	-	140
Global effects		130	10	3	-	-	-	-	-	-	140
Damage abroad	a b	-[g]	-[g]	-[g]	120 1280	-	340 880	-	-[h]	520 210	970 2370
TOTAL	a b	130	10	3	200 2180	-	440 1150	4	30	2190 900	3000 4400

Footnotes on the following page

[a]According to many international studies, the health effects caused by particulates dominate the total damage. However, it is not yet known which composition of particulates or size distribution is the most harmful. Some identifications have been made between PM_{10}/sulphate/nitrate contents and mortality/health effects. It is obvious that although the PM_{10} content is usually used as an indicator, sulphate and nitrate originated from SO_2 and NO_x emissions have some part in the damage. On this line the health effect assessed on the basis of the PM_{10} content has been regarded as caused by particulate emissions.

[b]On this line the health damage assessed on the basis of the PM_{10} content has been divided between particulates (40%), SO_2 (50%) and NO_x (10%). The percentage figures are based on the fact that the PM_{10} content measured in the Metropolitan area consists of sulphate (approx. 50%), nitrate (about 1/10) and unanalyzed matter (approx. 40%). There is substantial uncertainty in the magnitude of the effect and the distribution between different components.

[c]The summary report of the SIHTI project did not give any valuation for health effects caused by nitrogen oxides. This assessment is based on the relationship between the nitrogen dioxide concentration and respiratory symptoms identified by Schwartz and Zeger.

[d]The summary report of the SIHTI project gave a considerably higher figure because PAH emissions from small-scale burning (boilers of <1 MW) had also been taken into account. Here the small-scale burning PAH emissions are omitted, so that the figure illustrates the damage caused by energy production units of >1 MW.

[e]This figure is somewhat higher than that in the summary report of the SIHTI project. This is due to the fact that the statistical cases caused by VOC emissions of particulate compounds were expected to have already been taken into account in the estimated cases caused by particulates, in which case the damage calculated to be caused by particulates was corrected downwards.

[f]The summary report of the SIHTI project did not give any estimate for ozone-caused fores decline. So far, there is limited information about the effects of ozone on forests. The estimate that is a part of these figures has been calculated using the preliminary estimate of the UN/ECE of forest growth decline caused by exposure to ozone.

[g] The damage attributed to greenhouse gases is shown on the line "Global effects".

[h] Information about NMVOC emissions from energy production affecting abroad was not available.

The figures are results of calculation examples. The assessment shows the order of magnitude of the damage and the impacts of energy production emissions which are of potential significance. However, it has not been possible to assess all arising impacts. Ecological effects in the urban area (parks, etc.) and health effects in the rural area were not taken into account. The damage to buildings and constructions of considerable culture historical significance have not been estimated. The landscape value of forests and the value of biological diversity were not estimated.

The dashes in the table indicate that the component in question is likely to cause damage, but it has not been possible to estimate the value of this damage. In addition to the components in the table, the damage to waterways caused by nitrogen and phosphorous was estimated at approx. FIM 18 million/a.

Adding the results contains a risk of overestimation, since especially the values of health effects are based on different WTP studies, which take into account only the WTP to avoid a certain effect. In that case a possible (simultaneous) willingness to pay to avoid other effects and the impact of this on available funds (budget) will not be taken into account. This could not be taken into account in the SIHTI project, and it was supposed that the WTP to avoid all effects is the same as the sum of the expressed WTPs to avoid individual effects.

The split between the fuels used in energy production is shown in the Table II. The damages have been divided into effects in population centres, urban areas and globally and the damage (other than greenhouse gases) arising abroad.

4.2 ASSESSING THE RELIABILITY OF RESULTS

Monetary valuation contains several uncertainty factors. The most significant problems with respect to the SIHTI study are the transferability of results from different conditions, the aggregation of results, uncertainty factors in the estimates and problems related to discounting.

The WTP estimates obtained earlier and in other countries than Finland using the contingent valuation method (related mainly to health effects) have been converted to Finnish marks (the 1990 value) by expressing the WTP estimate in the 1990 currency of the country in question by means of the consumer price index, and the value is then exchanged to Finnish marks using the purchasing power parity.

In some cases, care must be taken not to take into account the same damage twice, in which case the total damage would be overestimated. For example, damage to construction materials has been considered as a function of the sulphur dioxide concentration. Other emission components may also have caused some of the damage. However, reviewing the damages as a function of particle concentrations as well and adding this to the above damage value would result in overestimation since the sulphur and particle concentrations probably correlate.

TABLE II

Damage in population centres (health and material effects) in rural areas (ecological effects) and globally (climate change and thinning of the ozone layers). Total damage (FIM million/a 1990) and damage per energy content (FIM/MWh_{fuel} 1990) in parenthesis.

		Light Fuel Oil	Heavy Fuel Oil	Coal	Natural Gas	Peat	Wood	Σ Av.
Health and material effects	a	300 (17)	90 (12)	1010 (31)	5 (0,3)	130 (18)	210 (24)	1740 (20)
	b	190 (10)	280 (39)	1030 (31)	30 (2)	120 (16)	100 (12)	
Ecological effects		10 (0,6)	20 (3)	80 (2)	10 (1)	10[c] (2)	10 (1)	140 (2)
Global effects		20 (1)	10 (1)	60 (2)	20 (1)	10 (2)	20[d] (2)[d]	140 (2)
Abroad	a	50 (3)	60 (8)	770 (23)	50 (3)	30 (4)	10 (1)	970 (11)
	b	210 (12)	420 (58)	1450 (44)	130 (9)	140 (18)	30 (4)	2370 (27)

[a] See footnote a of table I

[b] See footnote b of table I

[c] In addition to this, the damage caused by discharges from energy production is estimated at FIM 18 million/a.

[d] In case the used wood is offset by new growing trees so that the same amount of carbon dioxide that is released during firing is bound back to the ecosystem, the net emissions and the damage can be estimated at nil

Uncertainty is associated with several phases of the monetary valuation procedure. The estimated amounts of emissions may contain uncertainty (for example PAH). Relationships between emissions, concentrations and depositions (e.g. particulates, sulphate, nitrate) are not known with certainty. In addition, it may be difficult to estimate the proportion of a certain emission sector or source among the total concentrations. The average dose people are exposed to is also difficult to estimate. Furthermore, dose-response functions often include a great amount of uncertainty. However, in this connection it should be emphasized that in Finland there has been little research on health effects, which would be of importance for this study, ie relationships between the air quality of population centres and mortality/cancer morbidity, or the effects of respirable particles in general.

"Discounting" is used to make future benefits and losses comparable to present benefits and losses. In the case of the fuel cycle this is an important part of the valuation, since many environmental hazards caused by today's operations will arise after several years. The higher the interest, the lower the value which is given to these losses. This study uses consistently a discount rate of 3 %, which can be seen as a compromise choice (the 3 % rate has also been used in the ExternE and US/DOE projects).

In general it can be said that on the scale "very uncertain - uncertain - fair - good" none of the assessments is better than "fair" in reliability.

4.3 EFFECT SPECIFIC ASSESSMENT OF THE RESULTS

The estimates of the external costs obtained during the SIHTI project are primarily the results of the example calculations. Even though they include many uncertainty factors, they indicate the magnitude of the damages and also what effects and components are potentially the most significant. On the basis of the calculations made, health effects dominate the damage caused by emissions from energy production. The estimated damage of health effects would be in the range of billion Finnish marks (FIM billion/a), whereas forest damage and crop losses would both be lower by a factor of ten (less than FIM 0.1/a) and the same with global impacts. However, it is somewhat surprising to find that health effects so clearly dominate, while ecological effects and global effects are astonishingly small. On the other hand, emission effects abroad and the damage due to sulphur dioxides and nitrogen oxides are mainly ecological effects. So, the total ecological effects are also of the order of billion Finnish marks annually (FIM billion/a).

One possible reason for the dominance of health effects is that the values are based on estimated WTP, while others are mainly based on market prices. For that reason, the value of a statistical life, ECU 2.6 million, has been used as a starting point to value the estimated additional death cases [5],[7]. The estimate has been corrected downward so that it would illustrate the expectancy value of a remaining life. In nearly all statistical cases the unit value arrived at was about ECU 6.7 million. The "unit value" to be used affects markedly the end result, and it would therefore be important to clarify in greater detail what value(s) should be used. In Finland the value used for traffic deaths is FIM 7.6 million. On the other hand, the values of buildings and constructions of considerable culture historical significance, the landscape value related to forests or the value of biodiversity have not been assessed. The assessment of global impacts contains a particular amount of uncertainty. It can also be pointed out that the ratio of WTP values to mere medical treatment costs has been approximately 2 - 3 for several health effects.

A great many health effect cases are excess deaths caused by air pollution. On the basis of the calculations made in the SIHTI study, fuel-induced emissions from energy production would cause about 80 deaths annually due to respirable compounds (about 20 cancer cases and about 70 cardiovascular cases) and some 50 cases through the food chain. According to the calculations, air pollution due to all emission sources would cause about 450 deaths due to respirable particles (about 100 cancer cases and over 350 cardiovascular cases) and over 150 cases through the food chain. As hydrocarbon emissions from wood firing have been omitted in this presentation, the number of deaths caused by fuel-induced emissions from energy production is calculated to be about 80 annually. In general, the valuation of health effects is associated with a considerable amount of uncertainty, in particular with regard to additional mortality due to respirable particles (and hydrocarbons) and additional morbidity due to respirable particles.

The proportion of the calculated materials damage in the total damage is small, as expected. Sulphur dioxide concentrations in Finnish population centres have been decreasing throughout the 1980s, which has reduced air pollution-induced corrosion. With regard to particulate-caused fouling, emissions from energy production are estimated to account for 5 % in the concentration of total suspended particulates. The fouling damage caused by the concentration of total suspended particulates is thus significant, about FIM 600 million. Construction materials damage as a function of the sulphur dioxide concentration was estimated on the basis of the thorough investigations carried out in the Stockholm area. The result obtained contains less uncertainty than the values of most other damages calculated in the SIHTI study. The fouling effect of particulates can easily be given higher figures, and it is therefore a matter of agreement how to determine the value of this damage per capita at different concentrations.

The low level of forest damage due to energy production emissions can widely be explained by the fact that the majority of acidifying sulphur (about 75 %) and nitrogen (80 %) comes from abroad, in which case the proportion of domestic emission sources remains small. On the basis of the calculations the total forest damage would exceed half a billion Finnish marks in 1990 (excluded possible damages caused by ozone). This is only 10 - 20 % of the figure which IIASA has arrived at when assessing forest damage due to sulphur emissions in Finland [10]. The estimated damage abroad caused by sulphur and nitrogen emissions from energy production is mainly ecological effects. The estimated value of forest damage is based on the example calculation which assumes that annual forest growth decline due to acidification would be 0.1 %/a during the next 100 years. No value could be calculated for ozone-induced forest damage in the SIHTI project. For this presentation I have made an example calculation based on the preliminary estimate of the UN/ECE, according to which a dosage of 10,000 ppbh (accumulated exposure in hours exceeding a threshold value of 40 ppb) would cause growth decline of 10 % for sensitive tree species. In the example calculation I have used a more cautious assumption, according to which a dose-response function would be linear and the 10,000 ppbh dosage would cause growth losses of 5 %.

The ozone which causes forest decline and crop losses mainly originates from elsewhere (90 %) than from emissions of energy production (10 %). Researchers begin to have an overall view of the dose-response functions of ozone-induced plant damages. The value of the plant damage caused by ozone contains a less amount of uncertainty than the other values calculated in the SIHTI study.

The total damage the Finnish energy production causes to recreation fishing has been estimated at about FIM 5 million a year and the cost of prevention of discharges from peat production into waterways at about FIM 18 million a year. The damage caused to pipings due to groundwater acidification was estimated at FIM 2 million annually (1990). The estimates with regard to waterways effects contain a great amount of uncertainty because of specific waterway features.

The damage caused by greenhouse gas emissions was estimated at FIM 150 million/a. Finland's proportion of the world's greenhouse gases is some tenths per cent, and energy production emissions account for 70 - 80 % of Finnish carbon dioxide emissions. The given estimate includes many uncertainty factors and not only because the greenhouse effect is a very complicated process, but also because any consequences from "global warming" are very difficult to assess. Another approach would be to value CO_2 emissions in monetary terms using economic instruments. One starting point would be to reduce CO_2 emissions to the level which Finland has committed to in international agreements. The society's WTP estimated in this way would seem to be higher per ton of carbon dioxide than the estimates per ton of emissions which some studies have arrived at.

The proportion of Finland's energy production in thinning of the ozone layer in the stratosphere was estimated on the basis of the thinning of the ozone layer due to greenhouse gases and the health effects caused by resulting increased UV radiation. The damage was estimated at FIM 1 million/a. The given estimate includes a great amount of uncertainty and not only because the impact of energy production gases on the ozone layer is not thoroughly known, but also because consequences from increased UV radiation on the globe is not possible to assess comprehensively. In addition, dose-response relationships are very uncertain.

When examining harmful effects due to different emission components (effects in Finland and abroad in 1990) the essential point is how to distribute the health effects assessed by means of dose-response functions which use PM_{10} content as an indicator among different emission components. In case they are distributed among SO_2, NO_x and particulate emissions in the same proportion as the measured PM_{10} concentrations in the Helsinki metropolitan area consist of sulphate, nitrate and non-analyzed substances, it can be learned that the damage caused by SO_2, NO_x and particulate emissions from energy production is dominant being in the range of billion Finnish marks (FIM billion/a). The damage caused by greenhouse gases would clearly be smaller (a couple of hundred million Finnish marks/a), and the damage caused by hydrocarbons and heavy metals would be insignificant in respect of the final result. As regards emissions of hydrocarbons, the situation may change if the review includes PAH emissions of small-scale energy production (boilers and furnaces of < 1 MW, mainly wood burning) as was the case in the SIHTI study.

The distribution of health effects attributable to respirable particulates between different emission elements also affects the size of the damage caused by different fuel chains. Irrespective of whether the damage is distributed in proportion to particulate emissions or in the above way among SO_2, NO_x and particulate emissions, the damage due to the coal chain and heavy fuel oil emissions per fuel energy content appear to rise highest (effects in Finland and abroad). The damage due to emissions from light fuel oil, peat and wood burning chains per energy unit would seem to be clearly smaller, and between them of the same order of magnitude. The damage caused by natural gas chain per energy content was clearly the smallest.

Existing foreign estimates of the external costs of wind power are clearly smaller than those for energy production based on fossil fuels and about the same order of magnitude as those for hydro power and photo-reactors. There is no particular reason to believe that the situation would be different for Finland.

Since the above results are based on the energy systems in use in 1990 and the emissions level of the same year, it may turn out that the values calculated by the same method but using data from later years differ from those arrived at in the SIHTI study. Emissions from new plants which meet the stricter requirements for emissions (eg Meri-Pori coal-fired power plant) cause less damage on average per energy content than emissions from other power plants. When the effects of population centres are dominant, the same applies to the plants located further away from population centres, whose emissions are average. The 1990s have seen several significant investments in environmental technology, eg desulphurization plants and low NO_x combustion, which have not been taken into account in the calculations.

5. COMPARISON WITH ESTIMATES OF EXTERNAL COSTS OF WIND POWER

The external cost of wind power production in Finland has not been estimated to date. Using Danish estimates of the emissions (SO_2, NO_x, CO_2) in connection with the manufacturing and operation of a 500 kW wind power plant and the average unit damage values of our study indicate, that the damage per unit of electricity produced would be less than 1 FIM/MWh_e. Clearly, the construction of power plants using fossil fuels causes emissions as well. Those emissions were not considered in the estimates given earlier. Other impacts of wind power production are those of noise emissions and the impacts on flora, fauna and landscape. A Danish report [8] on the damage value of these effects, including those of air pollutants estimated the external costs of wind power to 1 - 12 DKK/MWh_e (1 ECU = 7,1 DKK). The central estimate for wind power, 0,5 DKK/MWh_e, was about 1 % of that for coal, about 2 % one of that for natural gas and about 10 % of that for biomass. The ExternE-project [1] has presented an estimate of the external costs of wind power of about 1,0 - 2,3 ECU/MWh_e, one order of magnitude less than for coal, oil and lignite. A English study [7] estimates the external costs due to health impacts of wind power to 0,4 £/MWh_e (1 ECU = 0,8 GDP) (other impacts were not estimated for wind power), which is one order of magnitude smaller than for coal and oil fired power plants and the estimated total costs of natural gas and CHP plants and half as big as the estimated total costs of solar power. Those impacts of hydro power that were estimated in the study were about as big in monetary terms as those of wind power.

6. CONCLUSIONS

The work done shows that it is possible to estimate the external costs of energy production caused by environmental effects of fuel cycle emissions. However, the accuracy of estimates regarding most effects is still very rough. Environmental economics including monetary valuation of environmental effects is now the focus of vigorous research in Europe and in the United States in particular, where the valuation of environmental effects is carried out to an increasing extent as part of the cost-benefit analysis of large-scale projects or to assess the value of environmental damage caused by accidents. In Europe several investigations concerning the subject are under way. Generally speaking, the field is in a development phase where valuation principles and methods are being developed and their applicability is being investigated.

Taking into account the external costs in future investment decisions and other energy policy choices would be desirable. Energy production has several effects, the costs of which are not fully included in the market price of energy. Energy producers or consumers do not pay these costs, but they will be covered by a third party, which often is society. Since the external costs cannot be seen in the costs of energy production, they are not taken into account when comparing the social or economic profitability of different forms of energy production and individual power production projects. Omitting the external costs is thus, in fact, a benefit to such an energy production form which causes the externality.

External effects are not necessarily environmental impacts but can also be related to the security of supply, employment, region development, etc. In general, environmental impacts are most difficult to determine. In Finland, there is an excise tax determined by the energy content and carbon content of a fuel, which affects the competitiveness of fuels and thus steer consumption. Generally speaking, the fees in question improve the market position of environmentally safer fuels (and domestic fuels), unless it is a question of simple fiscal payments. The amount of fees has, however, not been determined based on external environmental or other effects, which this paper assesses. Taking into account uncertainty factors, it is clear that it is not possible to apply this kind of assessment directly, but it would be desirable that the development of assessment methods would bring along the valuation of external environmental effects that could be one input factor when deciding on economic instruments (taxes and fees), at least to show the internal value of different effects. On the other hand, international emissions control agreements change the nature of the problem. If the countries agree to reduce their emissions to a certain level, the problem is how this would be done at the lowest possible cost from society's point of view. In this case, estimates of how expensive environmental effects are should affect decision making as early as targets are set. Taking account of the large geographical coverage of several emission components (greenhouse gas emissions and acid depositions, in particular), it is very important to agree on emissions limits internationally. It would be desirable that when determining limits for emissions, emissions taxes and environmental fees, the estimates of external costs would be one basis for the decision making as soon as economic valuation methods and calculations of external costs are sufficiently accurate.

Related to the above it would be important to develop methods and rules of the game for carrying out and applying economic valuations. On the one hand, input into research on the effects, on which there is not enough data for making reliable assessments (forest damage, several health effects), should be increased and on the other hand, new methods should be developed and common principles should be agreed on to assess damage caused by emissions. An example of a value to be agreed on is the value of a statistical life, which is used in different connections (e.g. road planning in connection with accidents causing death), but its magnitude varies considerably in different situations. In addition, the situations in which valuation techniques can be used should be defined. Besides environmental taxation, potential application areas are cost-benefit analysis to be made during governments' programmes and large projects. In manufacturing of certain products, energy is the most important production factor with regard to environmental effects and it should therefore be taken into account in life cycle analyses. In life cycle analyses, the environmental impact assessment is followed by the economic valuation of effects, which is one phase of the analysis.

The method developed in the SIHTI project by Ekono Energy Ltd and Soil and Water Ltd to value the external effects of energy production emissions is based on identification of damages with different effect areas, determination of suitable dose-response functions and application of market prices and WTP values. The most recent and high quality research results have been used to apply the method to the 1990 situation (amounts of emissions, concentrations and depositions). The work has shown that research must be continued and estimates must be made more accurate along with new available results from several areas of research. Each type of effect could be investigated in a separate study. The interdisciplinary nature of the work would require the coupling of researches from different fields to this work, which, however, was not possible within the budget of the SIHTI project.

Since the damages caused by energy production emissions are most obviously significant in monetary terms, it is justified to continue their research and economic valuation. Results and valuation methods should be checked whenever emission levels change or more accurate research results are published.

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The Environmental Costs of Wind Energy in Spain

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ABSTRACT: This paper summarizes the assessment of the environmental costs of the wind fuel cycle in Spain. It has been carried out within the ExternE Project of the European Commission, and so it has been done following a site-, technology-specific methodology. The main impacts identified have been noise, and the loss of visual amenity. As a result, we have obtained some values for the external costs of wind energy, which have shown to be much lower than those of conventional fuel cycles. It is also important to note that careful planning would avoid most of these costs.

1 INTRODUCTION

It is now widely accepted that electricity generation poses costs to society which are not included in the electricity bill, and thus, are not paid by the producers or consumers of electricity. They include, for example, the damages caused on forests by the operation of coal power plants, or the alteration of natural landscapes by the installation of wind farms.

Though some qualitative assessment of the damages is required in most countries, they are only useful to decide between the installation or not of a certain electricity generation system, or between the sites in which to install them. No objective comparison can be attempted between different generation options, as we are not using the same measuring unit.

This latter point is the goal of the ExternE Project of the European Commission, within which the present work has been carried out. It tries to device a common methodology, under which all the impacts (in the first stage, only environmental impacts) caused by the different electricity generation systems may be assessed in common units (actually, in monetary units) so that the full costs of each option may be compared on an objective basis, without need for the planner's criteria.

Full costs, or social costs, as termed in economic language, include private costs, that is, those accounted for by the producer, and external costs, or externalities, which are the ones imposed on society, not included in the electricity price. The quantification of these externalities is useful for planning or dispatching if the full costs of the energy options are to be taken into account. In addition, this quantification lets us know which are the true costs of electricity generation, which is the price society is paying for it.

The main difficulty in the assessment of external costs is, in most cases, the economic valuation of the impacts, as we are usually dealing with goods which are not traded in the market, and thus have no price assigned. How can we place a monetary value for human life, for example? Or how can we value in monetary terms the loss of bird population? This aspect may be controversial, but it is not, in our opinion, a major case for an argument against this methodology. As long as the same values or methods are being used for all the fuel cycles, they should not bias the comparison between them, which is the main objective of the project.

Many other difficulties arise along the assessment. Lack of adequate data, for example, makes it difficult either to identify and assess the consequences of the fuel cycle activities, or to quantify the damages they may produce.

In spite of all these problems, estimates for the external costs of fuel cycles are being obtained for many technologies and locations. Though they may not be yet full estimates, they are already giving us some clues about the full costs of each generation option, and how the current planning and dispatching patterns should change to incorporate them. In the case of wind energy, which is already competitive with conventional energy sources in some places, accounting for the full costs of electricity could further promote its widespread implementation.

2 METHODOLOGY

The methodology used in this study has been the one proposed by the ExternE Project of the DG XII of the European Commission. It is based on the damage function approach. Under this approach, we try to identify the burdens produced by the wind fuel cycle, and, following logical steps, the damages caused are measured and monetarized. These steps are clearly stated, in order to make the assessment process as transparent as possible, so that its advantages and disadvantages may be clearly identified, and sensitivity analyses are made easier.

The final objective is to produce monetary values for the damages caused, to be incorporated to the electricity price as adders. As prices, according to economic theory, should be treated on a marginal basis, these adders have to be calculated using a marginal approach. That is, we consider the externalities created by the implementation of an additional facility, with a specific technology and located in a specific site.

From this latter point it can be inferred that, under this methodology, no general values are to be obtained. Although general, mean values could be useful when dealing with global impacts, we feel it is not appropiate to use them for local or regional impacts, as the site and technology specificity makes them highly variable.

In order to compare between different fuel cycles, we have to study the whole fuel cycle, from manufacturing of the facility, to the transmission of the electricity. Once chosen a certain technology and location, all the existing burdens are identified, and then they are linked with the damages they produce in a matrix, which has been called accounting framework. In this matrix, all the burdens and damages should be included, even though they may be found later to be negligible, or impossible to quantify. This way, we are pointing to future research areas. The area and time period studied should be those along which there may exist some impact, regardless of the location or lifetime of the plant. It has to be remarked that, in this stage of the project, no external benefits or non-environmental costs have yet been assessed.

Each of the burdens and the corresponding impacts are linked by an impact pathway, in which the logical steps mentioned above for the damage function are clearly stated, from the identification of the burden to the economic valuation of the impact. This impact pathway may be more or less complex, depending on the existing interactions, or the nature of the impact. For example, the one for the loss of visual amenity produced by the installation of a wind farm is rather straightforward.

The quantification of the impacts is carried out using a variety of methods. It is important to note that these methods should be the same for all the fuel cycles, to ensure a consistent comparison. They include the use of statistical rates (which is against the marginal approach on a first look, but this problem can be avoided choosing the appropiate data), dose response functions, or computer simulation models. For the impact of the noise produced by the wind turbines, for example, a noise dispersion model is used.

One of the main sources of uncertainty existing in the assessment arises from the fact that most of this methods have been devised for specific conditions, and their transferability may be questioned.

The last stage of the assessment is the economic valuation of the damages. This is perhaps the most complicated part, as there is no price for most of the goods affected by the impacts, such as visual amenity, or human life. Then, alternative valuation methods are required, which can calculate the willingness to pay (WTP) for an improvement in welfare, or the willlingness to accept (WTA) a change for worse.

This is done by trying to create a ficticious market for the non-marketable goods. Direct methods, such as the contingent valuation method (CVM), ask directly the consumers for their WTP or WTA. Indirect methods, such as the travel cost method, or the hedonic pricing, try to obtain these values through related variables. The problem with these methods is that they are highly dependent on the conditions under which the study is carried out, so their transferability is also complicated.

Along the assessment, as can be easily seen, there are a considerable amount of uncertainty sources, from the lack of adequate data to the problems in the valuation of the impacts. When possible, this is reflected presenting a range of values for each of the estimates. For each impact, we try to point to these uncertainty sources, so that they may be solved by further research.

As a result of applying the methodology, we obtain the estimates for the external costs of the fuel cycle. As we mentioned before, some impacts are not quantified, so the results will probably be underestimated. However, for rather simple fuel cycles such as wind energy, we think that the estimates produced are very near to reality.

3 RESULTS

This study has assessed the external costs of a 3 MW wind farm sited in Galicia, in the northwestern corner of Spain. The wind farm has 20 wind turbines, of 150 kW each, with a medium tower height of 20 m. The yearly power output is 5,270 MWh.

The site is some 250 m away from the seashore, in a hill completely clear of vegetation. The nearest village is Camariñas, 4 km away from the wind farm.

The impacts have been classified according to the priority assigned to them by previous reports [1]-[4]:

- High priority impacts:
  - noise from the turbines
  - visual intrusion of the turbines and associated equipment.
  - occupational accidents in manufacturing, construction, and operation.
  - public accidents due to turbine operation and road travel.
  - global warming and acid deposition due to emissions from materials processing and component manufacturing.
- Medium priority impacts:
  - impacts of the turbines on birds
  - impacts of construction on terrestrial ecosystems
  - radio interference
- Low priority impacts:
  - visual intrusion to travellers
  - land use on agriculture

High priority impacts are treated in detail, and a valuation is attempted. Medium priority impacts are reviewed quantitatively, and low priority impacts are not considered.

In the following sections, the main results of our study will be outlined. Further comments may be obtained from the full report carried out for the ExternE Project [2].

3.1 NOISE

Noise from the wind fuel cycle can be generated by different sources: wind farm operation, construction, transport, etc. However, only the first source has been addressed, as it is considered the major problem.

A variety of studies have been carried out on this subject, but few monetary valuations have been attempted. We have based our estimations on the work of Gildert [3].

The noise produced by the wind turbines may create more or less annoyance, depending on:

- the wind turbine noise itself
- the turbine location
- the distance to inhabited areas
- the background noise

Typically, noise levels at nearby houses are lower than 40 dB. In the wind farm studied, only 8% of the resident population consider that the turbines make noise.

The noise level of the wind turbines at the nacelle is around 105 dB. To determine the noise perceived by the population, we have used a sound propagation model which takes into account the contribution of the whole wind farm, the distance to each household, the air attenuation, the background noise, the time of the day, and the intermittency of operation. The noise impact should also be corrected with the noise sensitivity of the population, its attitude towards wind turbines, its socioeconomic characteristics, etc.

The monetary valuation has been done using hedonic pricing methods, originally developed for traffic noise studies, so there is some uncertainty on their transferability. Damages are measured by applying a noise depreciation sensitivity index (NDSI), which estimates the depreciation of house prices as a function of ambient noise levels. The annual value of noise (AVN) due to the wind farm is calculated on the following expression:

$$AVN = \sum(L_o - L_b)*N*A(P)*NDSI \quad \text{, where}$$

L_o: observer's perceived noise level
L_b: background noise level
N: number of houses on that location
A(P): annuitised average house price

Introducing the corresponding data, we obtain an annual damage of 4.2 ECU, or 0.0008 mECU/kWh

3.2 VISUAL AMENITY

The impact of wind farms on visual amenity is the most subjective environmental issue of the wind fuel cycle, and the most difficult to quantify.

In our particular case, it does not seem to be very important, as only 14% of the resident population find that their visual amenity is negatively affected [4]. The main aspects that have to be taken into account for the assessment are:

- the characteristics of the wind farm: size, shape, colour, rotation speed, etc.
- the area from where the wind farm is visible
- the attitude of the observer: this is dependent on functional, social and aesthetical aspects. It has been shown that socioeconomic conditions, the level of information provided to the public, and their degree of involvement, affect considerably their attitude.

The economic valuation of visual amenity is commonly carried out using contingent valuation or travel cost methods. Unfortunately, they tend to aggregate landscape amenity values with other welfare benefits, such as tourism and recreation, thus resulting in a probable underestimation of the impacts.

It is expected that values will be affected not only by characteristics of particular sites, but by cultural considerations. This makes quite difficult their transferability.

In Spain, some valuation studies have been accomplished, but for different areas, mainly forests and recreation areas. We have used the lower estimate of a contingent valuation study for a montainous area, which was a WTP of 5 ECU per household [5]. This has resulted in an aggregated damage of 3.9 mECU/kWh, considering only the two villages nearer to the wind farm. This seems to be a very high value, when compared with other studies, and considering that only 14% of the population feel disturbed.

3.3 ACCIDENTS

We have calculated the impact of the accidents related with the wind fuel cycle on occupational and public health. They are treated separately, as the first ones may be internalized through labour or insurance markets. The stages to be assessed are:

- manufacturing of wind turbines
- construction of the wind farm
- turbine operation
- transport activities

The calculations have been made applying accident statistics to the reference data. There is an objection to this process, as no wind farm specific data are available with the appropriate statistic significance. Thus, data for similar activities have had to be used to provide an estimation, what results in some level of uncertainty.

With regard to general public, only traffic accidents have been considered, as it is expected that those produced by wind farm operation will be covered by the operators' insurance.

The monetary valuation is achieved using best estimates of accident damage, proposed by the ExternE Project [1]. The resulting values are shown on the following table:

TABLE I
ACCIDENT DAMAGE COSTS (mECU/kWh)

	Occupational acc.	Public accidents
Manufacturing	0.084	-
Construction	0.026	-
Operation	0.1	negligible
Transport	-	0.926
TOTAL	0.209	0.926

Previous reports have concluded that uncertainties in damage estimates are likely to be within an order of magnitude, what is a medium level of uncertainty.

3.4 RELATED ATMOSPHERIC EMISSIONS

If we are to compare different energy options, we have to analyze their full fuel cycles. That is why we have to assess the pollutant emissions related to the wind fuel cycle, even though there are no direct emissions in the operation stage.

The dominant users of energy, and therefore emitters to the atmosphere, are the materials processing and component manufacturing stages. Energy use in transportation, resource extraction, and construction, decommissioning and disposal processes is likely to be negligible.

According to the turbine composition, and to the energy values per weight unit of material, we have calculated an emission rate for each material. Linking emissions data and turbine material weight, we calculate the emissions produced by the turbine construction. Values have been obtained from Spanish institutions when available, and from British data when not.

For our case study, considering a lifetime of 20 years, the following results have been obtained:

TABLE II
POLLUTANT EMISSION RATES (g/kWh)

CO_2	SO_2	NO_x
14,92	0.143	0.059

There are several uncertainties in these results, due to the:

- omission of other fuel cycle stages
- use of foreign data
- assumptions made for energy use estimations
- uncertainties in emission factors
- uncertainties in component weights

However, it is estimated that the results should be accurate to within a factor of two.

For damage estimates, if it is assumed that they are proportional to emissions, the wind fuel cycle emissions are, as a fraction of the coal fuel cycle emissions factors, 1.7% for CO_2 and 13% for SO_2. If we use the estimates of the coal fuel cycle assessment of the ExternE Project for acidification and global warming, the estimated damages would be in the range of 0.01 to 1.03 mECU/kWh.

3.5 OTHER IMPACTS

1) *Impact on birds*

There is no clear evidence that wind turbines pose serious threats to bird population. Obviously, depending on the rotor height and speed, there is a potential damage to birds, but different studies have argued that it is not significant [4].

It is generally agreed that the greatest impact is caused on migrating birds, specially those who fly by night, as visibility conditions are an important factor. More than wind turbines, it is transmission lines which are responsible for more accidents, as they are less visible, and thus, less avoidable. It seems clear, then, that wind farms should not be installed on migration routes or sensitive species dwelling areas.

The only evidence in Spain of significant impacts is Tarifa, near the Strait of Gibraltar, which is a major migratory route. But here, it seems that particular circumstances come into account.

With regard to the wind farm studied for this report, it has not been found any effect on bird population [4], as resident bird population seem to have got used to it, and migration routes do not cross the wind farm.

2) *Impact on terrestrial ecosystems*

Wind energy is one of the energy systems which produce less damages on ecosystems. Only the effects of construction activities are of potential concern for terrestrial ecosystems, and in general these will be small and reversible.

As only 1-5% of the total area covered by the wind farm is actually occupied by the turbines, the deterioration of the environmental quality is almost negligible.

3) *Electromagnetic interference*

The moving turbine blades may produce electromagnetic interference. This happens because the reflected signal is both delayed and Doppler-shifted.

Many communication frequencies are potentially affected. However, communication systems are unlikely to be affected if the wavelength is greater that four times the total height of the turbine.

In practice, the area affected is limited to a shadow region of one or two kilometres long and a few hundred of metres wide [6]. Moreover, interferences may be rectified by a range of technical measures, at low cost.

4 CONCLUSIONS

Though some values have been produced for the most relevant impacts caused by wind farms, there are still many uncertainties underlying this assessment, what requires more research:

- noise dispersion models with a greater degree of accuracy are needed, so that calculations of perceived noise impact can be closer to observed reality.
- specific valuation methods for noise impact on rural locations have to be developed, as transferability from urban studies may cause a significant error.
- more valuation studies for amenity loss have to be carried out, in order to obtain adequate values with which to measure amenity changes in rural areas due to wind farms or similar constructions.
- careful attention has to be paid to socioeconomic conditions that may affect the general attitude towards different fuel cycles.
- a precise placement of accidents under public or occupational categories should be agreed, and the degree of internalization of them ascertained, in order not to fall in an overestimation of their impact.

The results obtained are summarized in the following table:

TABLE III
EXTERNAL COSTS OF WIND ENERGY (mECU/kWh)

Noise	0.0008
Visual amenity	0 - 3.9
Global warming	0.1 - 0.65
Acidification	0.01 - 1.03
Accidents	0 - 1.135
TOTAL	0.11 - 6.71

It can be concluded that the external costs of wind energy are very small, specially when compared with conventional fuel cycles. In the case of the conventional fuel cycle, which has been assessed by CIEMAT, external costs are an order of magnitude higher (2.04 - 66.66 mECU/kWh).

In addition, most of the external costs of wind energy could be avoided if the location of wind farms is carefully chosen, minding that they should not be sited:

- very close to population centres
- in areas of special scenic importance
- close to ornithologically relevant sites
- on important ecosystems sensitive to disruption by construction
- on communication system routes

This way, the external costs of well located wind farms will be negligible.

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INTEGRATING WIND AND SOLAR POWER INTO THE ENERGY SYSTEMS OF THE 21ST CENTURY

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ABSTRACT

Although they have been pursued by scientists and entrepreneurs for two decades, solar and wind energy have not yet claimed the large share of the world energy market that proponents hoped they would. Yet the past two years brought a series of developments that suggest the time has come for solar and wind energy to compete directly with fossil fuels. The next decade is likely to see the beginnings of a real energy revolution as the new energy sources are widely utilized for the first time.

Wind and solar power generators are likely to contribute significant power to the electricity systems of scores of countries within the next decade, with generating costs as low as 4-5 cents per kilowatt-hour. This will require adjustment in the operation of power transmission and distribution systems to accommodate intermittent resources, as well as new time-specific pricing of electricity. The transition to more open, competitive power systems, with liberal access by independent producers, is likely to speed introduction of the new technologies.

Altogether, the energy that strikes the earth's atmosphere in the form of sunlight each year, and the winds that flow from it, represent the equivalent of nearly 1,000 trillion barrels of oil--sufficient to fuel the global economy thousands of times over. By relying on a new generation of efficient, high-tech, and mass produced energy conversion devices such as advanced wind turbines and photovoltaics, the world can rapidly reduce its dependence on oil and coal in the twenty-first century.

In the more distant future, solar and wind energy have the potential not only to supply much of the world's electricity but to displace the direct use of oil and natural gas. Solar and wind energy can be used to split water via electrolysis, producing hydrogen gas that can be substituted for liquid and gaseous fuels. In this form, solar and wind power could be used to provide most of the energy needed for transportation, industry, and household use.

INTRODUCTION

The past year brought a series of developments that suggest the time has come for solar and wind energy to compete directly with fossil fuels. Major wind power projects were announced in India, China, Germany, and Argentina, to name but a few countries--setting off a boom in wind turbine construction. At the same time, tens of thousands of homes, found everywhere from Sri Lanka to Switzerland, were equipped with solar cells for electricity generation. A number of major corporations, including Enron, Westinghouse, and Siemens, brought new credibility to the renewable energy markets when they announced new investments in solar and wind energy technologies.[1]

With world leaders struggling to cope with problems such as urban air pollution, acid rain, and global climate change, pressure is growing to begin the transition to the world's two most abundant energy sources: the equivalent of nearly 1,000 trillion barrels of oil that strike the earth's atmosphere in the form of sunlight each year, and the winds that flow from it. Solar and wind energy are taking on a glossy, twenty-first century image, as countries from Germany to India seek to harness clean new energy sources that they can build their future economies on. The nineties are therefore becoming a breakthrough decade as countries around the world work to integrate sizable wind and solar developments into their existing energy systems.[2]

WINDS OF CHANGE

Wind power is on the verge of becoming a major new energy source. The world had more than 25,000 wind turbines in operation at the end of 1994, producing 3,700 megawatts of electricity. Denmark had roughly 3,600 wind turbines in operation, supplying 3 percent of the country's electricity; California had 15,000 wind turbines, generating as much power as the residents of San Francisco use each year. As the technology continues to improve and costs fall, wind power generation is now growing at more than 20 percent annually, with sizable wind industries developing in nearly a dozen nations.[3]

In the early eighties, wind machines typically cost $3,000 per kilowatt and produced electricity for more than 20¢ a kilowatt-hour (1993 dollars). By the late eighties, the machines were larger and more efficient and their capital cost, including installation, had fallen to about $1,000-1,200 per kilowatt. At an average wind speed of 5.8 meters per second (13 miles per hour) and a maintenance cost of a penny per kilowatt-hour, this yields a generating cost of 7-9¢ per kilowatt-hour for U.S. wind turbines installed in the early nineties, compared with 4-6¢ for new plants fueled by natural gas or coal.[4]

More than a dozen American and European companies, many with government assistance, are pursuing advanced wind technologies that are believed capable of closing the remaining cost gap with fossil fuel plants. According to one study, the average capacity factor of Californian wind turbines--the percentage of their annual power potential generated--rose from 13 in 1987 to 24 in 1990. These machines are now estimated to be "available" to operate 95 percent of the time, which is better than most fossil fuel plants.[5]

The machines now entering the market generate 300-750 kilowatts per turbine rather than the 100-kilowatt average of the late eighties' models. They have lighter and more aerodynamic blades made of synthetic materials, improved rotor-hub connections and drive trains, new blade controls, and more advanced power electronics, including some that operate at variable speeds, which allows the turbines to run more efficiently in a range of winds. The new designs are less expensive and can be deployed in more moderate wind regimes. In 1994, wind developers using the new technology signed contracts to sell wind-generated electricity for as low as 4-5¢ per kilowatt-hour.[6]

As wind has gained acceptance as an economical source of power, a number of U.S. utilities have begun to incorporate it into their plans. Sizable wind power projects are being built or planned in Iowa, Maine, Minnesota, Montana, New York, Oregon, Texas, Vermont, Washington, Wisconsin, and Wyoming. In California, a major debate is underway over some 1,500 megawatts' worth of projects that were bid successfully in a 1994 auction but are now being fought by the utilities.[7]

In northern Germany, a relatively high power-purchase price established in the early nineties allows private wind power developers to receive up to .17DM (13¢) per kilowatt-hour for their electricity. As a result, Germany added 300 megawatts of wind capacity in 1994, making it the world leader. And in the United Kingdom, power companies are required to reserve a portion of new power contracts for "non-fossil" sources, a provision intended for nuclear power but now benefiting wind energy. Greece, Spain, and the Netherlands have ambitious plans as well.[8] Altogether, members of the European Union aim to install 4,000 megawatts of wind power capacity by 2000 and 8,000 megawatts by 2005. By the end of 1994, more than 1,400 megawatts were already in place in Europe, and the figure could reach 2,000 megawatts by the end of 1995.[9]

In India, a major wind boom was under way in 1994, as the government opened up the power grid to independent developers, and offered tax incentives for renewable energy development. By the end of the year, 100 megawatts of wind power had been added. Most of the projects involve joint ventures with European and U.S. wind power manufacturers who are now rushing to sign up local partners and break ground on assembly plants. One result: land values in areas of Tamil Nadu jumped to between 8 and 20 times previous levels.[10]

Although wind power still provides less than 0.1 percent of the world's electricity, it is fast becoming a proven power option, considered reliable enough for routine use by electric utilities. In many regions of the world wind is now fully competitive with new coal-fired power plants, and experts predict that as wind turbines enter mass production, costs should fall to less than \$800 per kilowatt (below 4¢ per kilowatt-hour, including operating costs) by the end of the decade, and perhaps one day to \$600 per kilowatt or 3¢ per kilowatt-hour, making wind one of the least expensive electricity sources.[11]

Even excluding environmentally sensitive areas, the global wind energy potential is roughly five times current global electricity use. Since the power available from wind rises with the cube of the wind speed, most of the development will occur in particularly windy areas. In the United States, wind turbines installed on 0.6 percent of the land area of the 48 contiguous states--mainly in the Great Plains--could meet 20 percent of current U.S. power needs. Indeed, even resource estimates that exclude large environmentally sensitive areas, show that three states--North and South Dakota and Texas--could in theory supply all the country's electricity.[12]

Among the countries that have enough wind energy to supply most or all their electricity are Argentina, Canada, Chile, China, Russia, and the United Kingdom. Egypt, India, Mexico, South Africa, and Tunisia should be able to push their reliance on wind power to 20 percent or more. Europe as a whole could obtain between 7 and 26 percent of its power from the wind, depending on how much land is excluded for environmental and aesthetic concerns. At least 20 small subtropical island countries have nearly constant trade winds that could meet a large share of their electricity needs, replacing the expensive diesel generators they now rely on.[13]

Relying on wind power as a major energy source will inevitably generate some land use conflicts. On the plus side, while it is true that wind farms would "occupy" large areas (1 percent of the land of the United States to supply one third of the country's electricity), most of it would be land where few people or wildlife reside. Moreover, wind machines occupy land mainly in a visual sense. The area surrounding the turbines can be used as before--usually for grazing animals or raising crops--and provide farmers with supplementary income. In Wyoming, for instance, a hectare of rangeland that sells for $100 could yield more than $25,000 worth of electricity annually. In many windy regions, harnessing the wind might enhance land values by acting as a windbreak and reducing soil erosion.[14]

One constraint to reliance on wind power is the distances that separate some of the world's large wind resources from major population and industrial centers. This problem is seen clearly in the United States, where nearly 90 percent of the country's wind resource is in the Great Plains, more than 1,000 kilometers from Chicago and 2,000 kilometers from New York or Los Angeles. In some cases new transmission lines will be needed to carry wind energy to where it is needed, or existing lines will have to be beefed up, perhaps using new FACS or superconducting ceramic wires, each of which is under development.[15]

The economics of remote wind power also appear favorable. A 2,000-kilometer, 2,000-megawatt transmission line would cost roughly $1.5 billion, which would add only about a penny per kilowatt-hour to the cost of wind energy. This would still allow wind to be fully competitive even with the cheapest coal-fired power. To ensure that the new power lines operate at close to capacity, wind farms may need to be packaged with gas turbine or hydropower projects that can be operated when the wind isn't blowing.[16]

SOLAR POWER HEATS UP

In the 1870s and 1880s, at the height of the Industrial Revolution, French and U.S. scientists developed an array of solar cookers, steam engines, and electricity generators, all based on a simple concept: a parabolic-shaped solar collector that is coated with a mirrored surface to reflect light coming from different angles onto a single point or line. These include parabolic "dishes," which resemble satellite television receivers, and trough-shaped parabolic collectors that concentrate sunlight onto a tube rather than a single point. By the turn of the century, inventors had built a wide array of solar engines but most were abandoned with the advent of cheap oil.[17]

Seven decades later, in the aftermath of the 1973 oil embargo, parabolic solar dishes and troughs made a comeback, as scores of scientists and engineers developed new designs. Though their efforts were not as well funded as the larger power towers, the results have been more promising. Late-twentieth-century inventions such as inexpensive reflective materials, improved heat transfer fluids, more-efficient solar receivers, and electronic tracking devices have greatly improved the effectiveness of a nineteenth-century technology, allowing engineers to reduce the cost of these systems.

The most successful effort to commercialize solar trough technology was launched in Israel in 1979. Arnold Goldman designed a system of mirrored troughs 9 feet high and 40 feet long to concentrate the sun's rays onto oil-filled tubes that run parallel to the mirrors along their focus. The troughs are mounted on a device that allows them to follow the arc of the sun, keeping it focused on the collection tube. The hot fluid can be used to produce steam and generate electricity.[18]

Using this design, Goldman's company, Luz International, built several solar power plants in southern California's Mojave Desert in the late seventies. The Luz plants now convert 23 percent of sunlight into electricity during peak sunny periods and 14.5 percent on an annual basis. Spread over 750 hectares, the solar plant produces enough power for about 170,000 homes. By burning natural gas as a backup fuel, Luz is able to keep its turbines running even when the sun is not shining. The cost of electricity from these plants is 9¢ per kilowatt-hour, far below the 29¢ from Luz's first plant in 1984. Between 1984 and 1990, Luz installed nine plants with a capacity of 354 megawatts of generating capacity, making it one of the top 10 Israeli exporters.[19]

Falling electricity prices and the vagaries of a tax-incentive-driven market drove Luz into bankruptcy in 1990, but the company's nine plants continued to churn out power in the Southern California desert. Belgian investors purchased the rights to the technology from Luz's creditors, calling the reorganized company (which is still based in Israel) Solel. In 1994, Solel was working to raise the efficiency and improve the storage of its systems, while rumors were rampant of negotiations under way to build one or more 200-megawatt solar power plants, possibly in Brazil, India, Israel, or Morocco.[20]

Other research teams also are developing solar troughs, including an innovative design by David Mills of the University of Sydney. Tests reveal that improved collector surfaces, polar axis tracking, and a better trough design can increase sunlight collection by nearly one fourth. By also adding vacuum insulation to the heat-carrying pipes, Mills estimates that the annual efficiency of the system may reach 20 percent, with peak efficiency between 25 and 30 percent. The new design has the ability to run for eight hours without sunlight by storing heat in an inexpensive bed of rocks, and to provide power for around 6¢ a kilowatt-hour.[21]

The parabolic dish collector is also mounting a strong comeback. Each dish follows the sun individually, with double-axis tracking that allows sunlight to be focused onto a single point where heat can be either converted directly to electricity or transferred by pipe to a central turbine. Parabolic dishes are generally more thermally efficient than troughs. Moreover, since dishes (like troughs) are built in moderately sized, standardized units, they allow generating capacity to be added incrementally as needed. And they can attain temperatures three to four times that of trough systems, thus producing higher quality steam and more electricity.[22]

The U.S. Department of Energy expects parabolic dishes to produce power for 5.4¢ a kilowatt-hour early in the next century, and some experts believe that such systems will outperform troughs economically. One system has been designed at the Australian National University, and an initial 2-megawatt plant was being built in 1994 in Australia's remote Northern Territory. The project is being funded by a consortium of electric utilities under pressure to reduce their heavy reliance on coal. Twenty-five dishes will feed steam to a turbine to produce power for the isolated community of Tennant Creek.[23]

Given the rocky development path that solar thermal energy has followed so far, it is difficult to anticipate the course of future developments. Low fossil fuel prices have cooled the interest of utilities, but the attractions of a new pollution-free power source, coupled with the niche markets opening up in many countries, may be sufficient to spur a takeoff. A 1994 World Bank study concluded that solar thermal power plants would be economical in many developing countries; in response, the Bank is working on a solar initiative aimed at financing such projects.[24]

One possibility that is being explored in the U.S. Southwest is to convert existing coal-fired power plants into solar thermal power stations that use natural gas for backup--already close to being economical for plants that face legal requirements to cut the amount of sulfur and nitrogen oxides they emit, according to one set of calculations. Another possibility is to link a field of solar troughs or dishes to a gas turbine power station, allowing the solar collectors to substitute for the boiler in a combined-cycle plant, which would increase the overall efficiency.[25]

The sheer abundance of solar energy suggests that it will be the foundation of a sustainable world energy system a century from now. Indeed, if we could harness just one quarter of the solar energy that falls on the world's paved areas, we could meet all current world energy needs comfortably. Moreover, according to several studies, solar thermal technologies should be able to provide power at 5-7¢ per kilowatt-hour by 2000, which could be broadly competitive with electricity derived from fossil fuels.[26]

THE ELECTRONIC REVOLUTION COMES TO SOLAR

During the past few years, the basic energy needs of some of the world's poorest people have been met by what is arguably the most elegant and sophisticated energy technology yet developed. A quarter of a million households in developing countries get their electricity from solar photovoltaic (PV) cells, which can be used in everything from handheld calculators to suburban rooftops and large desert power stations.[27]

Solar photovoltaic cells are semiconductor devices made of silicon--similar to but far less expensive than the chips used in computers--that convert the energy from sunlight into moving electrons, avoiding the mechanical turbines and generators that provide virtually all the world's electricity today. Starting in the late seventies, governments and companies invested billions of dollars in advancing the state of photovoltaic technology. By the eighties, solar cells were deployed at telephone relay stations, microwave transmitters, remote lighthouses, and roadside callboxes--applications where conventional power sources are either too expensive or not reliable enough.[28]

The technology continued to advance during the next decade, and by 1993 the wholesale price of photovoltaics had dropped to between $3.50 and $4.75 a watt, or roughly 25-40¢ a kilowatt-hour, thanks to both higher efficiencies and more automated manufacturing processes. As costs fell, sales rose--from 6.5

megawatts in 1980 to 29 megawatts in 1987 and then to 60 megawatts in 1993. The worldwide industry, including activities such as retail sales and installation, did about $1 billion worth of business in 1993.[29]

Although still too expensive to compete head-to-head with conventional generating technologies, photovoltaic cells have found ever-larger niches in the global energy market. The technology's versatility was best demonstrated in the mid-eighties, when Japanese electronics companies came up with an ingenious new application, attaching tiny solar cells to handheld pocket calculators and wristwatches. These require only a trickle of electricity, well within the capability of a small solar cell--even when operating in a dimly lit room. Since the late eighties, the Japanese have sold an average of about 100 million such devices each year, an application that absorbs 4 megawatts of solar cells annually, 7 percent of the global market.[30]

By the early nineties, thousands of villagers in the developing world were using photovoltaic cells to power lights, televisions, and water pumps, needs that are otherwise met with kerosene lamps, lead-acid batteries, or diesel engines. More than 200,000 homes in Mexico, Indonesia, South Africa, Sri Lanka, and other developing countries have obtained electricity from rooftop-mounted solar systems over the past decade. Most of these efforts have been pioneered by nongovernmental organizations and private businesses, with only limited support by government and aid agencies. In Sri Lanka, $10 million is enough to electrify 60,000 homes, estimates Neville Williams, founder of the Solar Electric Light Fund, a U.S.-based nonprofit that facilitates PV electrification in Asia and Africa.[31]

Still, solar electrification projects start with a large disadvantage, since most developing-country governments heavily subsidize the extension of grid electricity to rural areas, as well as the installation of diesel water pumps. Simply levelling the playing field--reducing the subsidies to conventional power or providing equivalent funding for solar energy--could lead to a boom in solar electrification. Slowly, a growing number of Third World governments and international aid agencies have begun to respond to this need, mainly by setting up new ways of funding solar power projects. One of the biggest success stories is in Kenya, where during the past few years, 20,000 homes have been electrified using solar cells, compared to only 17,000 homes that were hooked up to the central power grid during the same period.[32]

Some of the recent impetus has come from the Global Environment Facility (GEF), a fund set up in 1990 under the joint management of the World Bank, the United Nations Development Programme, and the United Nations Environment Programme to finance projects that are not quite economical today but that could benefit the global environment by keeping carbon dioxide and other pollutants out of the atmosphere. In Zimbabwe, a $7-million GEF grant approved in 1992 will finance a revolving fund to electrify 20,000 households in five years; another $55-million World Bank loan and GEF grant will support a program to install 100,000 solar lanterns and other projects in India.[33]

The World Bank is also making or considering solar loans to China, Indonesia, the Philippines, and Sri Lanka. Some of the new grants and loans are to strengthen nascent PV industries in developing countries, which can create economic opportunities and jobs in rural areas. The Zimbabwe grant, for example, supports six small PV installation companies and a larger enterprise that imports cells and assembles them into commercial panels.[34]

The use of solar electric systems in rural homes is growing in industrial countries as well, spurred by the popularity of vacation cabins and the cost of reaching them with power lines, which in the United States runs between $13,500 and $33,000 per kilometer for even small local distribution lines. By contrast, a 500-watt PV system--enough to power an efficient home's lights, radio, television, and computer--would cost less than $15,000, including batteries for storage. Norway already has 50,000 PV-powered country homes, and an additional 8,000 are being "solarized" each year.[35]

Electric utilities are beginning to serve the remote home market as well, in effect redefining their structure to include potential users who are not actually connected to the utility's web of power lines. In the rugged mountains and remote basins of the northwestern United States, the Idaho Power Company is purchasing, installing, and maintaining PVs for homeowners located off the grid. Instead of a bill based on electricity use, customers pay a set monthly fee based on the cost of installing and maintaining the system.[36]

As costs decline further, photovoltaics will begin to serve the $800-billion annual global market for grid-connected power. The world's electric utilities install 70,000 megawatts of generating capacity each year. If the PV industry were able to garner even 1 percent of this market, annual production of solar cells would rise tenfold. Capturing 10 percent of this market would allow a hundredfold increase in production.[37]

Prices will need to be cut by a factor of three to five before grid-connected applications become economical. Most PV experts believe that such reductions can be achieved via advances in cell efficiency and manufacturing processes and by capturing the cost-savings of mass production. In late 1994, Enron Corp, a major natural gas company, formed a partnership with the Solarex Corporation to begin large-scale commercial manufacturing of advanced thin film photovoltaics. The companies project that they can reduce current PV costs by a factor of at least four, and are making plans to install hundreds of megawatts of grid-connected solar power plants in the United States, India, China, and Pakistan.[38]

INTEGRATING INTERMITTENT RENEWABLES

Solar and wind energy technologies are now economical for many applications throughout the world. The remaining challenge with these intermittent generators is integrating them into the electricity grid. In the past, engineers have argued that fluctuating energy sources would create havoc in their systems, and require costly investment in backup generators or storage. But experience to date with wind generators in California and elsewhere suggests otherwise. Wind power has been easily integrated into the existing mix of generators--reaching as high as 20 percent of the total in some regions--and has actually increased the reliability of a few systems.

Still, utility engineers must deal with the fact that intermittent renewable power sources do not fit easily within the traditional hierarchy of generators. The challenge of integrating intermittent renewables into a grid is in many ways similar to one that utilities mastered long ago: meeting the rapidly fluctuating demands of customers. California's Pacific Gas and Electric Company has shown that a diverse array of intermittent power sources can meet one third of a utility's load at no additional cost, and up to one half at an additional cost of only 10 percent. The ease of integrating these sources depends in part on how well their availability matches patterns of consumer demand; experience shows that while in some regions peak winds coincide nicely with peak power demand, in others they do not.[39]

If intermittent power sources are to supply 20 percent or more of a region's electricity, adjustments may be needed, however. In regions with extensive hydropower, such as the northwestern United States, little if any additional backup is required since hydro provides a reserve supply. In addition, new gas turbines are sufficiently inexpensive that they make economic sense even if operated partly on standby, raising the possibility that in the future, independent power producers might build combination gas-turbine and wind-turbine plants, providing an attractive combination of high reliability and low installation and operating costs.[40]

As reliance on renewable energy sources grows, backup storage will be needed in some areas. The most commercially ready alternative is pumped hydro storage, in which electricity produced during low demand is used to pump water up to a reservoir from which it is released to generate power when demand is high. Another alternative is compressed air storage, in which underground rock fractures are filled with high pressure air. A third option is to store heat in hot rocks, water, or another medium, which can then be used to keep the system's turbines running long after the sun has set. Studies show that heat storage can extend the operating period of such a plant by several hours at only minor additional cost. Even more revolutionary storage technologies are on the horizon: tiny mechanical flywheels and superconducting magnets that can be used to economically store electricity within individual buildings.[41]

Although intermittent renewables will continue to present challenges for utility engineers, most are amenable to economical solutions. In the end, with the help of new electronic controls, renewables are likely to improve both the reliability and cost-effectiveness of many utility systems.

The amount of land required for renewable energy development is modest. To provide as much solar energy as the world currently gets from hydro and nuclear power combined, the world would need an area about the size of Costa Rica or Bhutan. Supplying the same amount from wind energy would require an area the size of Vietnam. (In this case, most of the land could be used simultaneously for other purposes, such as raising crops and livestock.) The land needed for solar and wind development is in each case small enough that environmentally sensitive areas can be withheld without significantly diminishing the available energy.[42]

THE POLICY CHALLENGE

Heavy subsidies for coal, research budgets dominated by unpromising nuclear technologies, and uncompetitive market structures are among the extensive barriers to harnessing a new generation of wind and solar technologies. Carl Weinberg, the former director of R&D at the Pacific Gas and Electric Company, and Princeton University scientist Robert Williams note: "The rules of the present energy economy were established to favor systems now in place. Not surprisingly, the rules tend to be biased against solar energy."[43]

The needed policy changes number in the hundreds, but most fall into one of five categories: reducing subsidies for fossil fuels and raising taxes on them to reflect environmental costs; redirecting R&D spending to focus on critical new energy technologies; accelerating investment in the new devices; rechanneling energy assistance to developing countries; and opening previously closed energy markets to more participants and greater competition.

One priority is to spur the expansion of commercial markets for technologies such as efficient electric motors, wind turbines, and fuel cells. Creating larger markets will encourage companies to scale up production and reduce the costs of these manufactured devices. As a general rule, each time cumulative production doubles, the average unit price falls 20-30 percent. For example, between 1909 and 1923, Henry Ford reduced the price of the Model T by two thirds, as annual production rose from 34,000 to 2.7 million.[44]

Solar and wind technologies are still in the early stages of cost reduction. Total production of wind turbines, for instance, was less than 2,000 units a year in the early nineties, while the largest manufacturer of fuel cells recently built a facility capable of producing just 200 intermediate-sized cells per year. Some of the most rapid cost gains are likely to come in photovoltaics, which since 1975 have dropped 33 percent in price for each doubling of cumulative production. The faster these markets grow, the more economical the technologies will become.[45]

One role for governments is to catalyze market-driven, multiyear purchases, so that production can increase through reliance on either direct purchasing programs or partnerships with industry. Solar generators, for example, could be purchased in bulk for use on military bases or government buildings. Following this model, the U.S. Department of Energy has established a Solar Enterprise Zone at its nuclear test site in southern Nevada, and plans to purchase 900 megawatts of solar electricity from the lowest bidders. The World Bank hopes to catalyze similar advances in developing countries through a Solar Initiative intended to finance large solar projects and bring costs down.[46]

Many of these measures will require recasting the role of government, which in the past has been more centrally involved in the energy sector than in almost any other part of the civilian economy. But in most areas, greater reliance on the market and less direct government involvement are called for. The concept that the government alone can invent a new energy technology and unilaterally push it to market--which was tried so unsuccessfully with nuclear power--is even less appropriate to renewable energy development. Government's main role is to facilitate commercial entry of new technologies.

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SCHEDULING AND RESOURCE ALLOCATION OF NON-CONVENTIONAL POWER SYSTEMS VIA MULTI LEVEL APPROACH

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Keywords: Optimization, Multi level, stochastic, deterministic, large scale system.

ABSTRACT

The objective of paper is to propose a design technique with a new economic dispatch analysis. This analysis are used the combined hierarchical approach & N.L. programming. There are three different energy sources which can be used to feed a remot area in Egypt desert: Wind source, PV and Desiel engine. The two sub-sources are considered here as: Batteries and water Basin. The load demand is to feed the suitable electric energy need for irrigation and domestic services. The optimization problem is composed of set of goals with set of constraints i.e we have a multi objective functions system had been studied as a large scale system. Using the developed technique, we can transform the complicated stochastic system into a simple deterministic one. The hierarchical technique is developed to study the large scale system for simplicity. The use of developed technique constitute a more forceful approach to find the minimum cost operating point with maximizing the total electric energy generated from the three energy sources. The method also gives greater flexibility in the selection of constraints, permitting the use of equality constraints as well as inequality one.

Introduction:

Despite the fact that the requirement of energy is continuously increasing, the presently declared recoverable oil reserves indicate the possibility that Egypt and many other Countries will be in shortage of Oil by the end of this Century. The energy crisis that faced the world in the 1970's forced almost all countries to reduce their use of fossil fuels in general and Oil in particular and led to the problem of thinking how to secure adequate energy supply at reasonable cost.

Therefore, new and renewable sources of energy seem to be the correct solution for the complicated problem of lag in energy specially in countries that have sources for these new type of energy. We know that Egypt is one of the countries that enjoys solar radiation all over its territories (average of 6Kwh/m per day) and favorable wind resources that can be used in generating electricity all over the country.

Also at Egypt, wind can be used as a source for generating mechanical or electrical power in a low price. That is why we think for new and renewable energy sources that depend mainly on natural sources:the sun and the wind which are available in Egypt

From point of view of new land, East Oweinat is a suitable area for the expansion of the agricultural land,it is located in the southwest of Egypt & covers a total area of about 9 million feddans. To realy estimate the value of East Oweinat, it is enough to know that the total present arable land in Egypt is around 6 million feddans.

The renewable energy sources at EO greatly exceeds the conceivable energy demand. Good wind potential with average speed of 7 m/s, that can produce approximatelly 1700 Kwh/m per year & about 3600 sunshine Hr./year at average insulation of 2570 Kwh/m per year, which compares with an irrigation energy requirement of 1800-2400 Kwh/ feddan per year. The only limitation on the use of these resources is the technical & economic viability of suitable energy conversion equipment. when a local electrical demand exceeding 100-200 Mw is created,it will begin to be worth considering the installation of a grid link to Aswan. The advantage is that all surplus power could be fed into the national grid,while power deficite could be met by the grid, [1].

The objective of this paper is to propose a design technique with a new economic dispatch analysis. This analysis are used the combined hierarchical approach and N.L. programming. [2,3,4]

There are 3 different energy sources which can be used to feed a remot area in Egypt's desert (EO): wind source, PV and desiel engine.The two subsources are considered here as:Batteries and water basin. The load demand is to feed the demand electric energy (for irrigation and domestice services) at this area.

The optimization problem is composed of set of goals with set of constraints. i.e. we have a multi objective functions system had been studied as a large scale system. [4,5] This paper describes a new economic dispatch analysis.

This analysis are used the combined multi-level technique and N.L. programming.

Depending on the type of the variables,the problem can be defiend. In other words the state variables with specified values give deterministic system. But,if the state variables have a probable values, the system is a stochastic one and it can not be studied by using the normal deterministic technique. Using the developed techniqu, we can transform the complicated stochastic system into a simple deterministic one.

The hierarchical technique is developed to study the large scale system for simplicity. The use of this developed technique constitute a more forceful approach to find the minimum cost operating point with maximizing the total electric energy generated from the 3 energy sources.

The method also gives greater flexibility in the selection of constraints, permitting the use of equality constraints as well as inequality one.

To conclude, different techniques have successfully been proposed in this research in order to solve both Stochastic and deterministic large scale multiarea electric power systems.

To overcome the difficulty of studying the stochastic system, apply the stochastic programming approach which mainly based on the chance constraint theory.

DESCRIPTION OF THE SYSTEM:

The system is composed of various electric renewable sources: PV source wind generator and Diesel engine to feed the required electric load of domestic services and irrigational EO.

To ensure the continuaty of this operation the system contains also battery system and water basin(as a reservoir for irrigation demand). The last two sources are operated at the shortage time, batteries as electric storage and the water basin as hydraulically one system analysis.

(I) DETERMINISTIC SYSTEM

1- Objective Function

The proposed objective function of the model is to maximize the total electric energy generated from the hybrid system and minimize the total cost at the some time. As shown that the system is multi objective one.

The first objective function is suggested as following:

Maximize:

$$F_1 = \sum_{i=1}^{n} E_{1i} + E_{2i} + E_{3i}$$

$$= \sum_{i=1}^{n} \sum_{j=1}^{m} E_{ij}$$

The second objective function is:

Minimize:

$$F_2 = C_1(E_1) + C_2(E_2) + C_3(E_3) = \sum_{j=1}^{m} C_j$$

as
$$E_1 = E_{SL} + E_{SB} + E_{SR}$$
$$E_2 = E_{WL} + E_{WB} + E_{WR}$$
$$E_3 = E_{DL} + E_{DB} + E_{DR}$$

where C_j is the cost of energy generated of source j and S,W,D, B,R,L are represented solar, wind, Diesel, Batteries, Reservoir, load systems respectively.

The Constraints of the System:

The problem is subjected to variaus physical and operational constraints. Some of these constraints are linear, while others are nonlinear in nature. It is observed also that the system has equality and inequality constraints [as cleared in other work is not puplished yet].

1- The Load Demand:

The generated energy must be related to the demand by the following relation:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} E_{ij} \geq D_i$$

2- Batteries:

a- for safty, the discharge of battery must not exceed certain limit (a) to prevent the damge for the batteries.

i.e $E_{BL} \leq a \cdot B \; n_i$

where a is max. limit for safty

B is the max. capacity of batteries

n_i is the number of auxiliary periods in interval i.

b- The mass balance equation of battery:

$$\sum_{j=1}^{n} E_{B_i} \geq (a + \delta_b) B . n_i$$

subsystem has its own variables besided the multipliers and coupling between each other.

At same time, this level is controled by the coordinator level untile give the optimal solution for this optimization control problem. [3].

Generally:

$$L_j = F_j + \lambda_{ij}\,(\text{constraint}) + \mu_{ij}\,(\text{constraints})$$

subsystem (1):

$$\begin{aligned} L_{1i} = E_{1i} &+ \lambda_{1i}\,(c_p E_{1i}) \\ &+ \mu_{1i}\,(E_{1i} + Z_{2i} + Z_{3i} - D_i) \\ &+ \mu_{6i}\,(\overline{E}_{1i} - E_{1i}) \\ &+ \mu_{6i}\,(E_{1i} - \underline{E}_{1i}) \\ &+ \lambda_{3i}\,(Z_{2i} - E_{2i}) \\ &+ \lambda_{4i}\,(Z_{3i} - E_{3i}) \end{aligned}$$

Subsystem (2):

$$\begin{aligned} L_{2i} = E_{2i} &+ \lambda_{1i}\,(C_w\ E_{2i}) \\ &+ \mu_{1i}\,(Z_{1i} + E_{2i} + Z_{3i} - D_i) \\ &+ \mu_{7i}\,(\overline{E}_{2i} - E_{2i}) \\ &+ \mu_{7i}\,(E_{2i} - \underline{E}_{2i}) \\ &+ \lambda_{2i}\,(Z_{1i} - E_{1i}) + \lambda_{4i}\,(Z_{3i} - E_{3i}) \end{aligned}$$

Subsystem (3):

$$\begin{aligned} L_{3i} = E_{3i} &+ \lambda_{1i}\,(c_d\ E_{3i}) \\ &+ \mu_{1i}\,(Z_{1i} + Z_{2i} + E_{3i} - D_i) \\ &+ \mu_{8i}\,(\overline{E}_{3i} - E_{3i}) \\ &+ \mu_{8i}\,(E_{3i} - \underline{E}_{3i}) \\ &+ \lambda_{2i}\,(Z_{1i} - E_{1i}) + \lambda_{3i}\,(Z_{2i} - E_{2i}) \end{aligned}$$

Subsystem (4):

$$\begin{aligned} L_{4i} = E_{4i} &+ \mu_{2i}\,(E_{4i} - a\,B\,n_i) \\ &+ \mu_{3i}\,(E_{4i} - (a - \delta_b)B\,n_i) \\ &+ \mu_{9i}\,(\overline{E}_{4i} - E_{4i}) \\ &+ \mu_{9i}\,(E_{4i} - \underline{E}_{4i}) \end{aligned}$$

where $E_{4i} = E_{1B} + E_{2B} + E_{3B}$

Subsystem (5):

$$\begin{aligned} L_{5i} = E_{5i} &+ \mu_{4i}\,(E_{5i} - b\,R\,n_i) \\ &+ \mu_{5i}\,(E_{5i} - (b + \delta_r)R.n_i) \\ &+ \mu_{10i}\,(\overline{E}_{5i} - E_{5i}) \\ &+ \mu_{10i}\,(E_{5i} - \underline{E}_{5i}) \end{aligned}$$

By using the suitable Non Linear Programming backage to solve the above optimization problem, all results are cleared at the conclusion section.

(II) STOCHASTIC SYSTEM:

As the insolation of the PV system has no specific value and the wind speed can not measured exactly and if also some variables of the other subsystems have no exact values, thus the system is not a deterministic system, it is a probablistic one or a stochastic system for simplicity, depending on the probability theories, the modefied technique is designed to study this stochastic problem by conversion into an equivalent deterministic one.

Subsystem (1):

where $\sum_{i=1}^{n} E_{Bi} = E_{BS} + E_{BW} + E_{BD}$

δ_b = the coefficient of charge losses for batteries.

3- Water Reservoir:

The same restriction as above, the energy equivalent to the amount of water needed should not exceed safty limit(b) to satisfy the reserve needed

a- $E_{RL} \leq b.R.n_i$

where R is the max.capacity of water reservoir.

b- The mass balance equation of water basin is:

$$\sum_{i=1}^{n} E_{Ri} \geq (b+\delta_r) R.n_i$$

where $\sum_{1}^{n} E_{Ri} = E_{SR} + E_{WR} + E_{DR}$

δ_r is the coefficient of water losses for water basin.

4- Boundry Limits:

$$\underline{E}_{ij} \leq E_{ij} \leq \bar{E}_{ij}$$

THE PROPOSED TECHNIQUE:

As Described above, the system is composed of eleven decision variables with intervals during the total time chosen T.

It can be observed that the problem formulation is rendered very complicated and required long time and large memory for solution.

A Decomposition of the problem will help making the problem amenable for solution especially if both of the number of energy sources (m) and the interval (n) are increased.

The hierarchical approach is the suitable one for these large scale system [2,3].

THE CASE STUDY FORMULATION:

To formulate the case study shown in fig(1) and by applying the two level technique described before, we have the following analysis.

The Lagrangian equation is:

$$\begin{aligned} L = F_1 &+ \lambda_1 F_2 + \mu_1 \left(\sum \sum E_{ij} - D_i \right) \\ &+ \mu_2 (E_{BL} - aBn_i) + \mu_3 \left(\sum E_{Bi} (a+\delta_b) Bn_i \right) \\ &+ \mu_4 (E_{RL} - bRn_i) \pm \mu_5 \left(\sum E_{Ri} (b+\delta_r) Rn_i \right) \\ &+ \sum \left[\mu_{6+j,i} \left[(E_{ij} - E_{ij}) + (E_{ij} - \underline{E}_{ij}) \right] \right] \end{aligned}$$

where L is the Lagrange equation

λ is the Lagrange multiplier

μ is the Kuhn Tuker multplier

a- The Coordinator Level:

To modefy the coordinators variables the following conditions are satisfied:

$$L_\lambda = 0$$

$$\partial L / \partial \lambda = 0.0$$

where $\lambda = [\ \lambda , Z\ ]$

as Z is the coupling variable.

b- The Subsystem Level

The large scale system is divided into 5 subsystems(PV, wind, Diesel, Batteries and the water basin).

Also, the Lagrange equation is divided between them and each

$L_{1i} = K_1 E_{1i} + K_2 (\sum^{n} \sigma^2)^{\frac{1}{2}}$
$+ \lambda_{1i}(K_1 \quad C_p E_{1i} + K_2 [\sum_1^n C_p \frac{\partial F_{2i}}{\partial E_{1i}} \sigma^2_{E_{1i}}]^{\frac{1}{2}}$
$+ \mu_{1i} \quad g_{1i} \quad (E_{1i})$
$+ \mu_{6i} \quad g_{6i} \quad (E_{1i})$
s.t. $+ \hat{\mu}_{6i} \quad \hat{g}_{6i} \quad (E_{1i})$
$E_{1i} \leq E_{1i} \leq E_{1i}$

where the coordinator Variables are μ_{1i}, Z_{1i} subsystem variables are: E_{1i}, λ_{ji}

The necessary conditions of the coordinator:

$$\frac{\partial L_1}{\partial \lambda_{1i}} \quad \frac{\partial L_1}{\partial E_{1i}}, \quad \frac{\partial L_1}{\partial \mu_{1i}}, \quad \frac{\partial L_1}{\partial \mu_{6i}}, \quad \frac{\partial L_1}{\partial \hat{\mu}_{6i}}$$

Subsystem (2):

$L_{2i} = K_1 E_{2i} + K_2 \sum^{n} (\sigma E_{2i}{}^2)^{\frac{1}{2}}$
$+ \lambda_{1i}[K_1 C_W E_2 + K_2 [\sum_1^n (C_W \sigma E_{2i})^2]^{\frac{1}{2}}]$
$+ \mu_{1i} \quad g_1 \quad (E_2)$
$+ \mu_{7i} \quad g_{7i} (E_{2i})$
$+ \hat{\mu}_{7i} \quad \hat{g}_{7i} (E_{2i})$
$+ \lambda_{2i} \quad g_{11i} \quad (E_{1i}, Z) + \lambda_{3i} g_{12i} (Z_{3i}, E_{3i})$

Coordinator Variables: $\mu_{1i}, \mu_{7i}, \hat{\mu}_{7i}, Z_{1i}, Z_{3i}$

Subsystem Variables : $E_{2i}, \lambda_{1i}, \lambda_{2i}, \lambda_{3i}$

The necessary variables: $\frac{\partial L_{2i}}{\partial \mu_{7i}}, \frac{\partial L_{2i}}{\partial \mu_{7i}}, \frac{\partial L_{2i}}{\partial \hat{\mu}_{7i}}, \frac{\partial L_{2i}}{\partial Z_{1i}}$

$$\frac{\partial L_{2i}}{\partial Z_{3i}}, \frac{\partial L_{2i}}{\partial E_{2i}}, \frac{\partial L_{2i}}{\partial \lambda_{1i}}, \frac{\partial L_{2i}}{\partial \lambda_{3i}}$$

Subsystem (3):

$L_{3i} = K_1 \, E_{3i} + K_2 [\sum^{n} \sigma E_{3i}{}^2]^{\frac{1}{2}}$
$+ \lambda_{1i}[K_1 \sum_1 E_{3i} + K_2 [\sum (C_D \quad E_{3i}^2)]^{\frac{1}{2}}]$
$+ \mu_{1i} \quad g_{1i} (Z_{1i}, Z_{2i}, E_{3i})$
$+ \mu_{8i} \quad g_{8i} (E_{3i})$
$+ \hat{\mu}_{8i} \quad \hat{g}_{8i} (E_{3i}) + \lambda_{3i} g_{12i} (Z_{2i}, E_{2i})$
$+ \lambda_{2i} \quad g_{1i} (Z_{1i}, E_{1i})$

coordinator variables: $\mu_{1i} \; \mu_{8i} \; \hat{\mu}_{8i}, Z_{1i}, Z_{2i}$

subsystem variables : $E_{3i}, \lambda_{1i}, \lambda_{2i}, \lambda_{3i}$

necessary condition: differentiation of L w.r.t all the above variables.

Subsystem (4):

$L_{4i} = K_1 E_{4i} + K_2 [\sum^{n} (C_B \sigma E_{4i})^2]^{\frac{1}{2}}$
$+ \mu_{2i} g_{2i} \quad (E_{4i}) + \mu_{3i} \quad g_{3i} (E_{4i}) + \mu_{9i} \, g_{9i} \quad (E_{4i}) + \hat{\mu}_{9i} \quad g_{9i} (E_{4i})$

where: coordinator variables: $\mu_{2i} \quad \mu_{3i} \quad \mu_{9i} \quad \hat{\mu}_{9i}$
subproblem variables : E_{4i}
necessary conditions : diff. L_{4i} w.r.t all variables : $\mu_{2i} \; \mu_{3i} \; \mu_{9i} \; \hat{\mu}_{9i}$

Subsystem (5):

$L_{5i} = K_1 \, E_{5i} + K_2 [\sum^{n} (C_R \sigma E_{5i})^2]^{\frac{1}{2}} + \mu_{4i} \, g_{4i} + \mu_{5i} \, g_{5i}$
$+ \mu_{10i} g_{10i} (E_{9i}) + \hat{\mu}_{10i} g_{10i} (E_{5i})$

Coordinator variables: $\mu_{4i} \quad \mu_{5i} \quad \mu_{10i} \quad \hat{\mu}_{10i}$

Subproblem variables : E_{5i}

Necessery Condions : L_{5i} w.r.t. $\mu_{4i}, \mu_{5i}, \mu_{10i}, \hat{\mu}_{10i}$ & E5

... variables distribution are shown in figures.

Results and Conclusions:

1- The deterministic formulation of the problem has lead to a complex optimization problem with multi objectives and set of inequality and equality constraints to be solved.
2- A new two level optimization algorithm has been developed using Nonilinear programming opproach.
3- Depending on the nature of the variables which have a probablistic values, a very complicated stochastic optimization problem has been obtained. To overcome this difficulty, applying the stochastic programming approach which is mainly based on the chance constraint theory. Thus this simple developed approach transform the problem into a deterministic one.
4- The sugested approaches have been applied to real case of EO.
5- Through the numerical simulation, it has been shown that the multilevel approach is more efficient than the global one, since it needs less computational time & memory storage.
6- It is cleared also that, the stochastic system need long CPU and bigger memory size than that needed in deterministic control problem.
7- The Demand load depend mainly on the electric energy generated from the renewable energy PV & wind to decrease the total cost.
8- The Diesel engine is used with other auxilary sources when the two other renewable sources can not satisfy the load demand.
9- The results cleared that the lowest cost can be realized by depending on the wind system,while Diesel engin is very costed.

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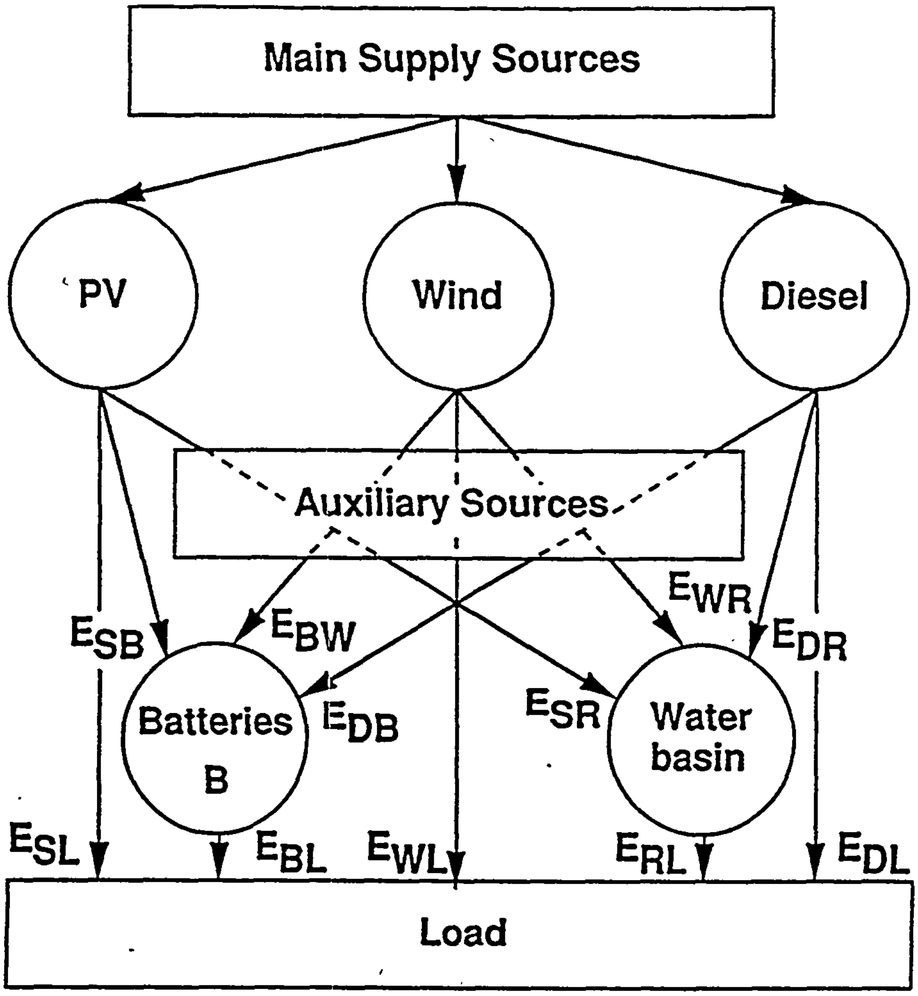
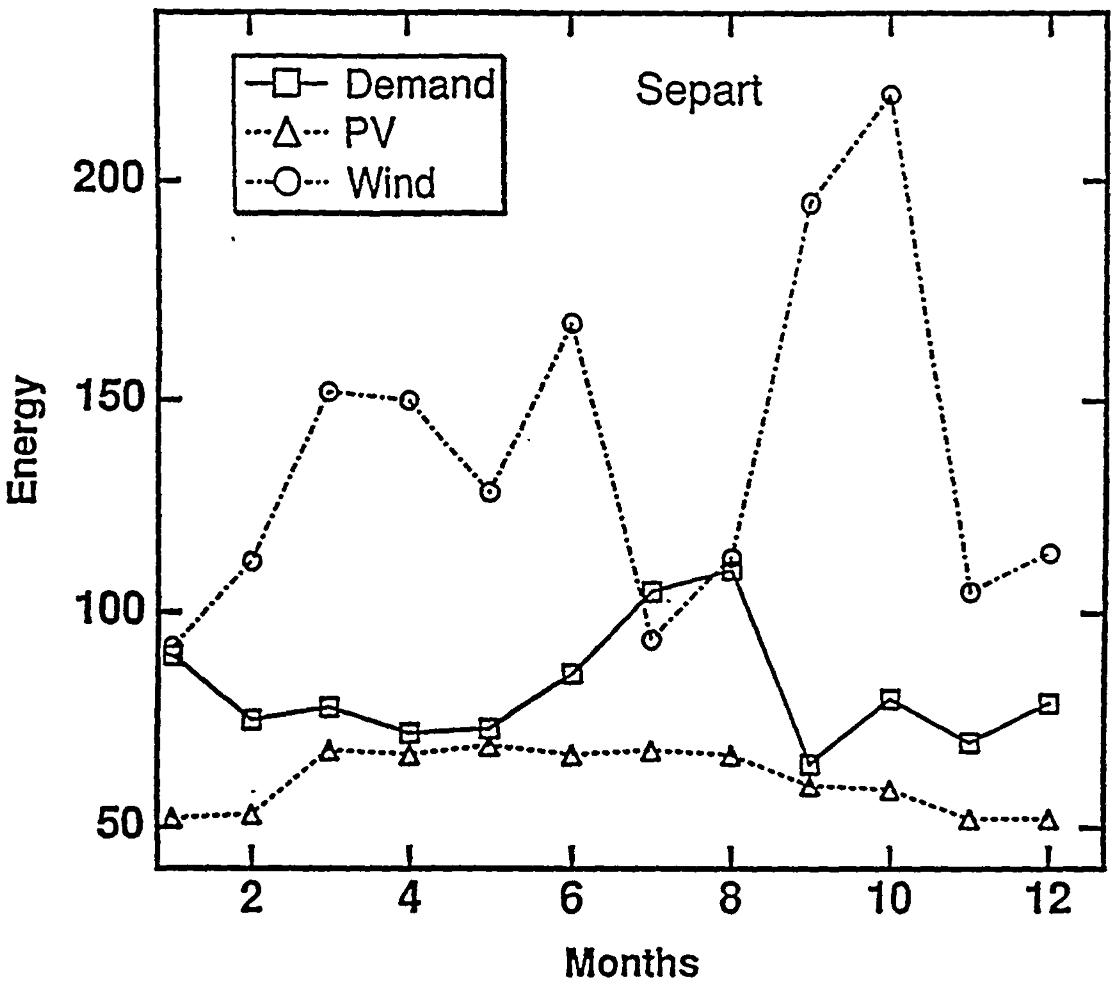
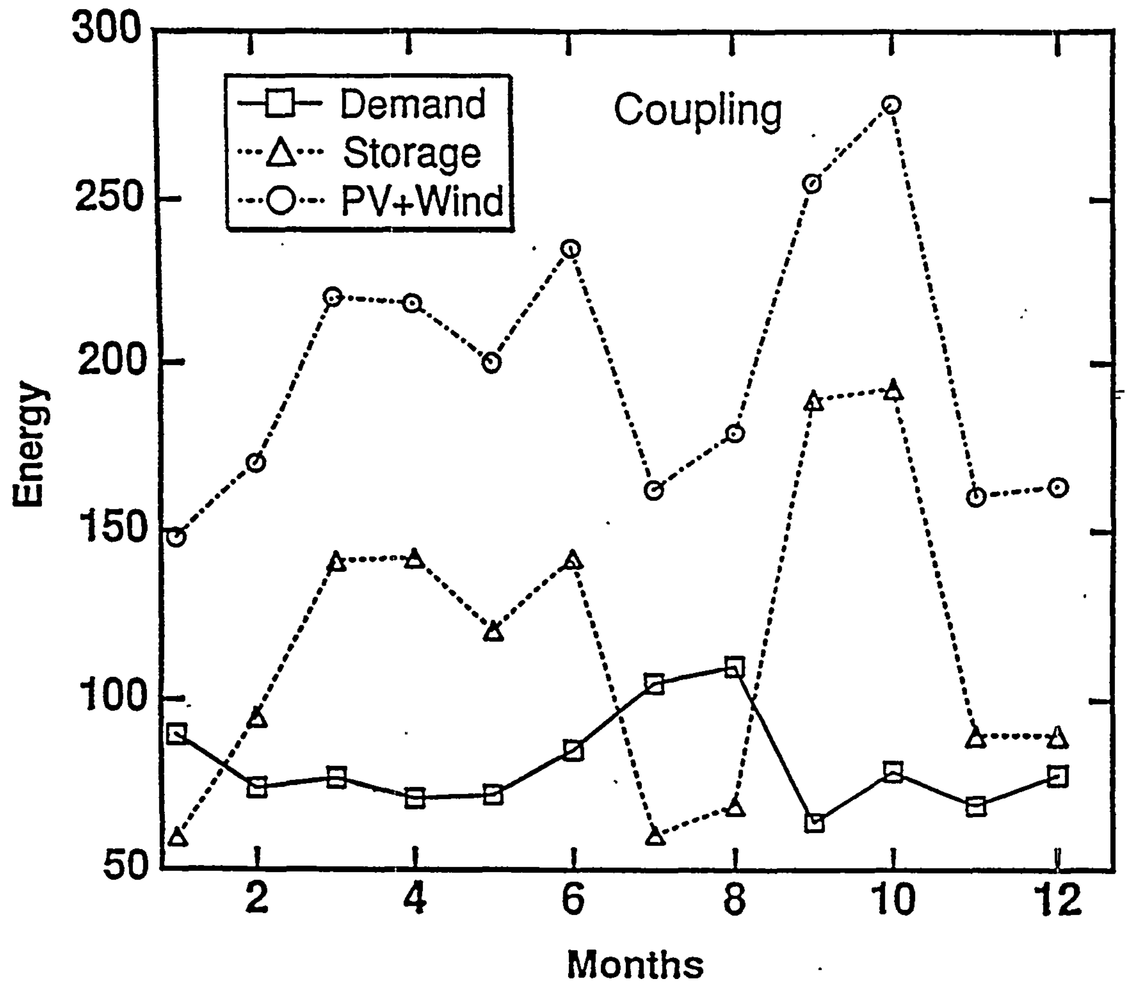


Main Supply Sources
PV
Wind
Diesel
Auxiliary Sources
E_SB
E_BW
E_WR
E_DR
Batteries
B
E_DB
E_SR
Water basin
E_SL
E_BL
E_WL
E_RL
E_DL
Load


Demand
PV
Wind
Separt
Energy
200
150
100
50
2
4
6
8
10
12
Months


300
250
200
150
100
50
Energy
2
4
6
8
10
12
Months
Demand
Storage
PV+Wind
Coupling

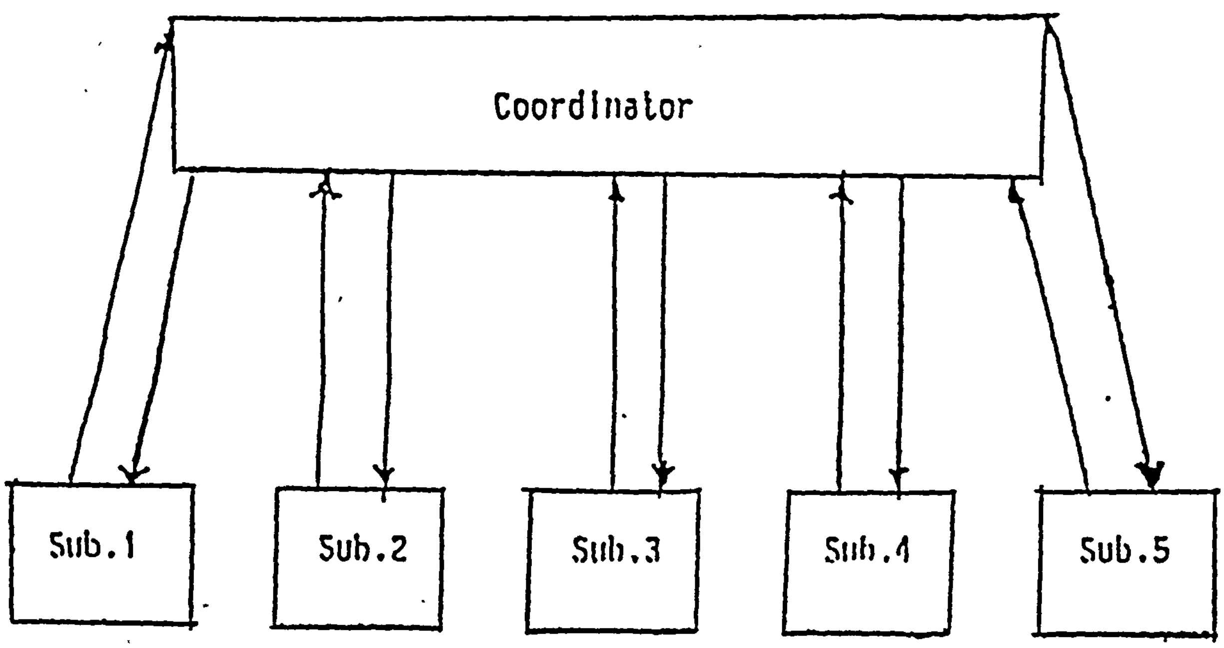


Fig (2) The variables distribution for the Hierarchical approach

Table I. Comparison between global & Hierarchal Techniques.

	GLOBAL		HIERARCHAL	
	Time (cpu)	Memory Size	Time (cpu)	Memory Size
STOCHASTIC	60	15	20	8 kw
DETERMINISTIC	47	10	12	16 kw
		Exact solution	The convergence between two successive iterations with in 10^{-5}. This technique is preferable for the large scale system.	

Energy Costs from European Wind Farms

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ABSTRACT Energy generation costs from European wind farms span a very wide range. Reasons for these variations, include differences in capital and operating costs, wind speeds and differing legislative and regulatory frameworks. This paper compares costs, wind speeds and discount rates for British and German windfarms and sets these alongside data from elsewhere in the European Union. In this way it is possible to determine the reasons for differences in energy generation costs.

1 INTRODUCTION

Wind energy prices in Europe appear to show wide variations, from about 5 cents ECU (in the United Kingdom), to 9 cents ECU (in Germany). Direct comparisons can be misleading since there are a number of reasons for these differences, in particular:-

- the state of maturity of the technology, which is affected by historical factors, such as the length of time incentives have been in place
- differences in capital and operating costs, partly due to the maturity of the technology, partly due to differing terrain
- differences in legislative and regulatory frameworks. British prices, for example are set by competitive bidding, German prices are fixed by law
- wind speed variations

There is, however, a large data base of information on wind farms in Denmark, Germany and the United Kingdom and the purpose of this Paper is to analyse this data, identify reasons for wind energy price variations and suggest ways of comparing data.

1.1 METHOD OF ANALYSIS

This paper draws on authoritative, public sources of information on wind farms built in Germany [1] and the United Kingdom [2] between 1992 and 1994. The level of detail available for the German wind farms is, in general, much higher. For most projects a detailed breakdown of costs was reported, whereas for the British installations only the total project cost was published. Table 1 summarises the details of the wind farms included in the analysis.

TABLE 1
GERMAN AND BRITISH WIND FARM DATA

LOCATION	UNITS 'Number/type/diameter/rating			SITE kW
GERMANY				
Otten	1 Sudwind	31	270	270
(Unspecified)	1 Micon	44	600	600
Brollingsee	7 Nordtank	37	500	3500
Rostock	4 Vestas	27	225	900
Prenzlau	3 WTN	26	200	600
Pfalz	12 Enercon	40	500	6000
Herrenkoog	12 Micon	44	600	7200
Hillgraven	7 Bonus	41	600	4200
Odenwald	3 Tacke	43	600	1800
Lindewitt	4 Tacke	43	600	2400
Fehnmarn	34 Enercon	40	500	17000
Vadersdorf	17 Vestas	39	500	8500
Dauer	3 Vestas	39	500	1750
GREAT BRITAIN				
Godmanchester	1 Vestas	27	225	225
Delabole	10 Vestas	35	400	4000
Carland Cross	15 Vestas	35	400	6000
Haverigg	5 Vestas	27	225	1125
Cemmaes	24 WEG	33	300	7200
Blood Hill	10 Vestas	27	225	2250
Rhyd-y-Groes	24 Bonus	31	300	7200
Chelker	4 WEG	33	300	1200
LLandinam	103 Mitsubishi	28	300	30900
Blyth Harbour	9 Windmaster	25	300	2700
Orton Airport	10 Carter	24	300	3000
Coal Clough	24 Vestas	35	400	9600
Cold Northcott	21 WEG	33	300	6300
Goonhilly	14 Vestas	35	400	5600
Llangwyryfon	20 WEG	33	300	6000
Ovenden Moor	23 Vestas	35	400	9200
Taff Ely	20 Nordtank	35	450	9000
Ramsy	1 Vestas	27	225	225
Kirkby Moor	12 Vestas	35	400	4800
St Breock	11 Bonus	37	450	4950
Bryn Titli	22 Bonus	37	450	9900
Caton Moor	10 HMZ	30	300	3000

2 COST AND PERFORMANCE COMPARISONS

Table 2 summarises and compares the performance and price statistics derived from the analysis. It may be noted that the British data covers about 80% of the installed capacity, whereas the German sample is smaller - but is representative of recent developments. The table also includes data from a Danish study [3]. The most striking features of the comparisons are:-

- British prices were significantly higher than those in Germany and Denmark, probably due to the lack of experience, but also due to the more difficult terrain.
- The much higher expectations of energy productivity in Britain, a reflection of the higher wind speeds.
- The higher wind speeds in Britain compensate for the higher project costs - prices per annual MWh are the cheapest in the Table

TABLE 2
DATA COMPARISONS

	GB	DE	DK (1)
Averages			
Machine size, kW	342	505	225
Machines in farm	18	8	-
Price, ECU/kW	1,362	1,210	1,173
Price, ECU/sq m	581	504	461
Price, ECU/MWh	508	566	595
Yield, kWh/sq m	1,143	890	775
Ranges			
Wind speeds, m/s	6.3-8.8	5.3-7.5	-
Price, ECU/sq m (2)	469-692	419-708	436-486

Notes 1 Danish study focused on 225 kW machines
2 Plus/minus one standard deviation

2.1 COST - SIZE TRENDS

The Danish data in Table 2 refers only to 225 kW machines and that study [3] notes that higher energy yields are derived from larger machines. The effect of this would be to increase Danish yields and reduce energy prices, which would move closer to the German levels. This adds weight to the assertion that savings are derived from the larger machine sizes. There is, however, considerable discussion over the precise merits of larger rotor sizes and the effect this has on the overall economy of wind energy. The British and German datasets were analysed in more detail to establish the significance of this trend and the results are shown in Figs 1 and 2. This shows project prices - in ECU per square metre of total rotor area - as a function of rotor power.

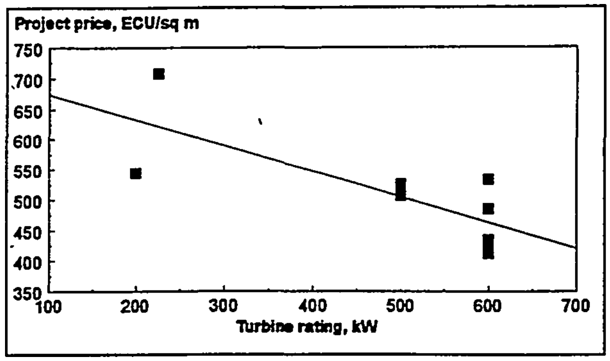

Fig. 1 Project prices and turbine size - Germany

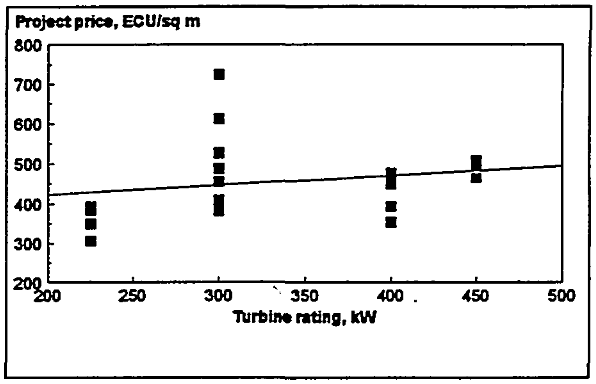

Fig. 2 Project prices and turbine size - Great Britain

Although there were insufficient data to establish definite trends, the German data (Fig. 1) indicates that prices fall with size and shows a stronger correlation (r= 0.77) than the British result (r= 0.20), which indicates prices rise with size. This apparently anomalous result for the U.K. may be due to the fact that the smaller developers, with lower overheads, tended to use smaller machines. In addition the larger machines tended to be used on the windier sites, which were more expensive to develop [2].

Further exploration of this question reveals:

- There is a very weak tendency for machine costs to decline with rotor area, as shown in Fig. 3. (Alternative ways of examining a link were explored, but similar levels of scatter were found when turbine price was linked to rated power and to diameter).
- As size increases, savings in foundation costs (Fig. 4) and operation and maintenance costs (Fig. 5) are acheived. This trend is much clearer and there is a stronger correlation.

Moreover, larger machines have greater hub heights and, therefore, higher energy capture. This accentuates energy price changes with size.

Overall, this analysis tends to confirm the hypothesis that the larger machines give lower energy costs.

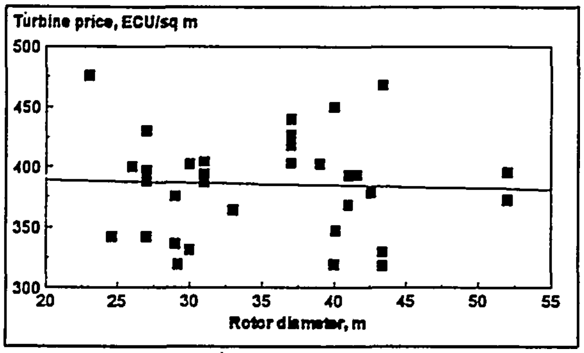

Fig. 3 Effect of size on turbine prices. (German data) There is much scatter and the correlation is weak

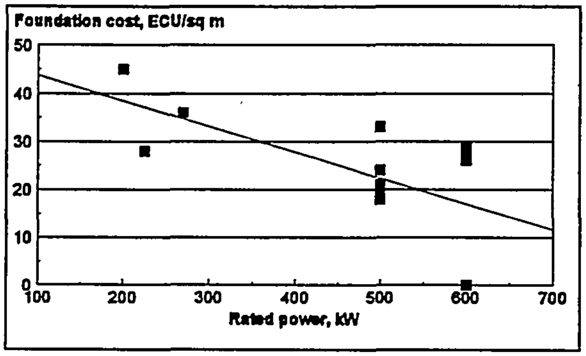

Fig. 4 Foundation costs as a function of rated power (German data) These clearly decrease with increase of size

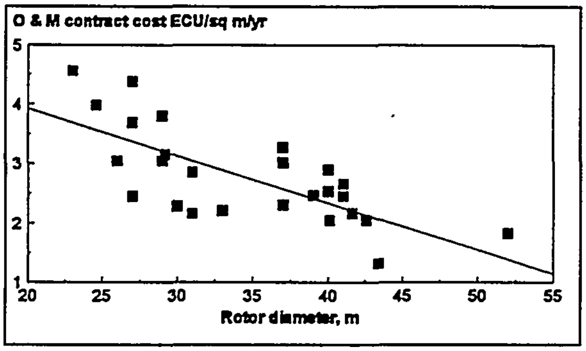

Fig. 5 Operating costs and rated power (German data)

2.2 COMPARISON OF CAPITAL COSTS

A comparison of the constituent cost of a wind farm reveals interesting variations (Fig. 6).

The German data have been drawn from the author's data base, British material from a recent analysis by ETSU [4] and the Danish data from [3]. The most significant features of the comparison are:-

- German machine prices appear significantly higher than Danish or British levels
- The costs for civil engineering, installation and grid connection all appear to be higher in Britain
- Overall costs are similar in Germany and Britain, lower in Denmark

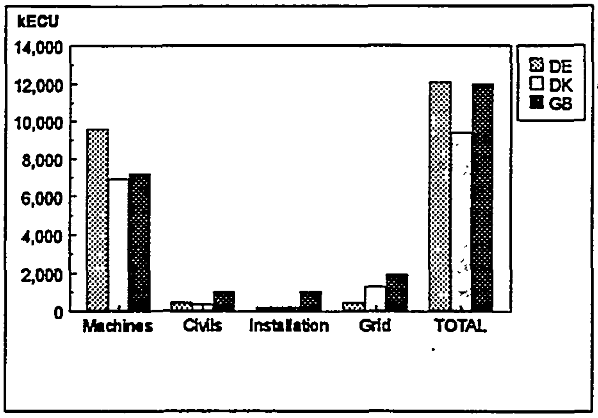

Fig. 6 Principal components of a 10 MW wind farm - price comparisons

Although the higher total costs in Britain may be due to the more difficult terrain, the fact that some component costs were higher implies that significant cost savings may be achievable

3 CURRENT WIND ENERGY PRICES

3.1 TECHNICAL FACTORS

Comparisons of current wind energy prices can be made using the more recent data from the German and British databases. In Britain, although further wind energy contracts have been announced under the third round of the Non-Fossil Fuel Obligation (NFFO3) no wind farms have yet been built. This comparison therefore uses NFFO2 data. To account for the rapid pace of development, installed costs one standard deviation below the average have been used, together with energy production levels one standard deviation above the average.

3.2 FINANCIAL FACTORS

In Britain and Germany most developments are carried out by privatised utilities or wind energy developers and capital is repaid within ten to fifteen years. Danish utility wind farms, on the other hand, tend to use longer repayment periods, related to the life of the plant [3].

Interest rates also differ. German wind projects tend to use low-cost finance from the Deutsche Ausgleichs Bank and the effective real rate for a complete project is around 8%. In Britain the effective rate is higher - around 10% [5], but Danish utilities use a rate around 6% [3].

Table 3 draws these performance and cost parameters together and shows typical wind energy price data for the three European states; it also includes American data drawn from an earlier analysis [5].

TABLE 3

WIND ENERGY PRICE COMPARISONS - 1994 VALUES

	GB	DE	DK	USA
Installed, ECU/sq m	470	400	380	360
Production, kWh/sq m	1,330	1,100	1,200	1,300
Real interest rate, %	10	8	6	9
Loan repayment (years)	12	12	20	20
Energy costs (cents ECU/kWh)				
Capital repayments	5.2	4.8	2.8	3
O & M cost	1.2	1.2	0.8	0.8
TOTAL	6.4	6	3.6	3.8

Fig. 7 includes a more detailed comparison between British and German prices, as a function of wind speed. Three estimates are shown:-

1. Great Britain: the upper curve links average NFFO2 project prices to NFFO3 contract terms, i.e. a 15 year contract period
2. - the lower curve assumes that NFFO3 projects can be built for 30% less than this Project costs are assumed to increase with wind speed in the same way as they did in NFFO2 [2].
3. For Germany, project costs in the lower quartile of the author's database are used. These are independent of wind speed.

It is clear that the higher windspeeds in Britain have a decisive effect in enabling low energy prices to be achieved but prices are otherwise similar

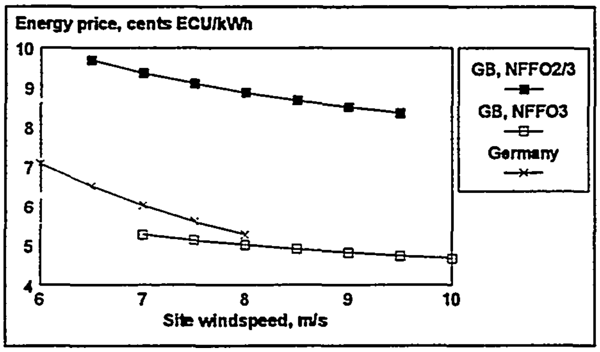

Fig. 7 British and German wind energy prices

4 PRICE CONVERGENCE

The relationship between wind energy prices and electricity prices from conventional fuels is examined in Figure 8. The comparator is the average selling price of electricity sold to industry, as defined by the IEA [6]. Wind energy prices in Britain are simply the contract prices for NFFO2 and NFFO3 respectively, the former recalculated to allow for a 15 year capital repayment period. German wind energy prices have been calculated by tracking the published price of a 500 kW machine over the period 1991 to 1994, adding 21% for balance of plant costs, and taking O&M costs as 2% of capital per year.

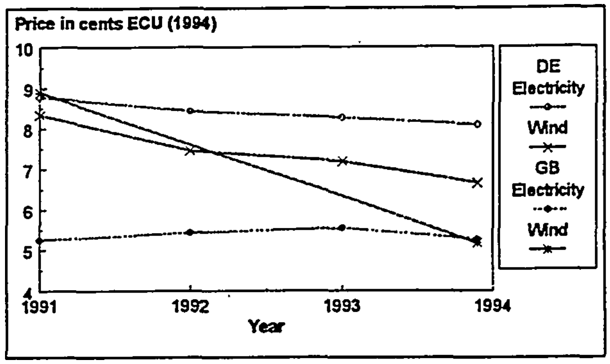

Fig. 8 Energy prices - wind and industrial electricity.

Prices have been rebased to 1994 levels using the retail price indices.

It is clear that wind energy prices are falling faster than industrial electricity prices in both Britain and Germany. The dramatic fall in British wind prices reflects the rapid maturity of the market but German wind energy prices are also falling more rapidly than industrial electricity prices. When the savings achievable by the use of larger machines and improvements in machine performance are also taken into account, it is probable that the wind price reductions in Germany have been understated

5 CONCLUSIONS

- It is clear that wind energy prices in both Germany and Great Britain are falling steadily - faster than the corresponding movements in industrial electricity prices.
- These trends seem likely to continue, aided by the development of larger machines. These enable significant savings in ancillary costs and operations to be realised
- The legislative framework in Germany facilitates developments at sites with lower wind speeds than the U.K. Energy prices, at sites with similar wind speeds, are comparable.
- British ancillary costs appear to be higher than those of Germany and Denmark, possibly due to the more difficult terrain.

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THE ALTERNATIVES OFFERED BY WIND ENERGY FOR SUPPORTING REGIONAL DEVELOPMENT IN EASTERN CANADA

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In Canada and more specifically, in the Quebec province where hydroelectricity is largely developped, the very low cost of electricity is making the wind energy a difficult choice. Despite this breaking context, the collapse of mega-projects and the needs of communities for alternatives or complementary sources of energy are rapidly pushing ahead a significant interest for wind energy.

A first wind plant is just implemented on Magdalen Islands. Two other similar projects are planned in Eastern Canada. But new type of wind developpers are emerging: for example the city of Rimouski in order to reduce the electricity cost of waste water treatment, fish plants which incure high freezing costs, small industries, farmers, ...

The profitability of these various alternatives and economic studies are key elements for the private and public deciders. The presentation will expose various recent approches used in Eastern Canada in order to help communities to make the best choice coping with their needs and capacity.

As a matter of fact, wind energy is becoming an important perspective of redynamization of the economy and industry in peripherical regions of Eastern Canada. Considerable decrease of fish industry fortunately occurs in very high wind potential regions (St. Lawrence corridor) and lead to consider wind industry and projects as a pertinent economic alternative to support and create jobs.

So, if in a short term perspective, wind energy is fighting with difficulty against low rates of hydroelectricity, on a long term basis, and in front of the necessity for the regional industry development (based on a sustainable development concept), the wind energy appears extremely interesting.

AN IMPROVED MARKET PENETRATION MODEL FOR WIND ENERGY TECHNOLOGY FORECASTING

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ABSTRACT: An improved market penetration model with application to wind energy forecasting is presented. In the model, a technology diffusion model and manufacturing learning curve are combined. Based on a 85% progress ratio that was found for European wind manufactures and on wind market statistics, an additional wind power capacity of ca 4 GW is needed in Europe to reach a 30% price reduction. A full breakthrough to low-cost utility bulk power markets could be achieved at a 24 GW level.

1 INTRODUCTION

The present wind energy capacity in the world is around 4 GW_n which corresponds to about 0.03% [1] of all electricity generating capacity worldwide. In some countries and regions, wind energy has already reached a much higher fraction, e.g. in Denmark 3.5%. A market share of a few per cent would already indicate early penetration into the major utility market [2], wheras lower fractions typical in most European countries, correspond to demonstration or public introduction programs.

The technology cost is one of the most important factors that effect the market penetration. For wind energy, the direct cost depends much on local conditions and is in Europe for new plants typically 4-6 ECU cents/kWh. This still clearly exceeds the price of raw electricity which has a price level of 2.5-4 ECU cents/kWh. To enchance wind energy diffusion into the market, a major cost reduction (or a cost increase of traditional fuels) is still necessary.

In a historical perspective, the price gap between wind energy and traditional electricity production has been reduced over the years. Wind technology has shown a major technical and economic progress since the early 80's and the price has dropped from those times up to now by a factor of 4-5 and the trend is still favourable [3]. This is mainly to be accounted by the learning processes inside the wind industries as wind energy does not yet benefit of economies of scale in manufacturing.

One of the main questions in the coming years for wind energy and its future is how well will it costwise perform, and followingly, how will the market penetration and production volumes develop over time. This set of questions is becoming very relevant for wind power as it is truely approching the MW-scale technology applicable mainly to utilities. Once a strong competitive foothold in the utility market would be established, a full breakthrough could follow.

Outgoing from the interesting "quasi-breakthrough" stage, or transient market situation, in which wind energy is in Europe today, we have in this paper tried to study analytically the market development of wind energy in Europe over the next decade and to some extent even beyond that.

In analyzing the penetration of an embryonic energy technology such as wind energy, it is important to account for possible technological improvements. Therefore, we combined manufacturing learning curves and diffusion theory to yield a new approach to market forecasting. The new model is then used for studying the conditions for penetration in Europe and some scenarios are presented. Finally, a penetration case scenario for Finland is built.

2 METHODOLOGICAL APPROACH

The basic approch used in this study is illustrated in Fig. 1. In this model, the technology costs and development are linked with the market size and the market dynamics.

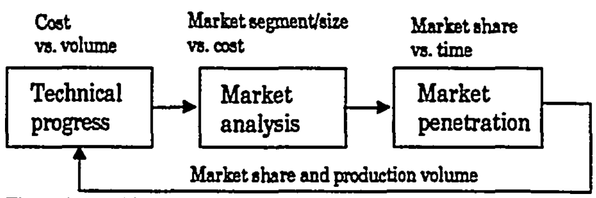

Fig.1 A combined technology and diffusion model for analyzing market penetration of wind technology.

The combined market theory described above does not include per se information on the means by which the price reductions can be realized. In case of wind energy the path is, however, possible to predict. Three main factors are found:

- increased wind energy production
- improved wind technlogy
- consideration of fuel cycle externalities

Thus, moving to more complex terrains, or, siting the wind parks better, yields higher wind speeds and hence higher wind production; component improvements and their integration with larger unit-sizes drop technology costs and material demands; external costs increase the price of electricity of competing energy sources.

2.1 DIFFUSION MODEL

The penetration of a technology or industrial innovation into the market, or market segment, can be presented through a diffusion model [4]. A simple model for manufacturing and industrial products also applicable for energy sources [2,5,6] is given in the following:

$$\frac{dF}{dt} = \alpha \times F \times (1 - F) \tag{1}$$

which after integration yields

$$F(t) = \frac{1}{1 + e^{-(\alpha t + \beta)}} \tag{2}$$

where α=capture rate of the new technology, β =integration constant, and F=market share. The coefficient α represents the penetration rate. The take-over time of the new technology, e.g. the time required to increase the share from 10% to 90%, is obtained from (2) as

$$\Delta T = \frac{\ln 81}{\alpha} \tag{3}$$

The equation represented by (2) is a typical S-curve and is characterized by three states: embryonic, growth and saturation. In some cases, the overall penetration may consist of multiple diffusion, i.e. of several S-curves. Such a situation could be perceived when technology jumps occur e.g. when moving into MW-scale turbines, or, when moving into new market segments. These transitions may cause also temporary saturation of the market.

2.2 LEARNING CURVE

The increase of the productivity in industries is typically gained through experiences in production. Cost reductions are due to basic improvements in production, exogenic improvements e.g. through R&D and customer feedback, and the economies of scale.

The productivity increases can be described by so-called learing curves that relate the unit costs of a product with the cumulative output [7]. The learning curve can be written as follows:

$$C_N = a \times N^{-b} \tag{4}$$

where C_N=the cost of the Nth unit, N=cumulative number of units produced, a=the cost of producing the 1st unit, and b=a parameter measuring the reduction of costs.

The learing curve is characterized through the progress ratio, $P=2^{-b}$. Each doubling of the cumulative output leads to reduction in unit cost to a percentage, P, of its former value. Typical progress ratios for manufacturing industries range from 0.75 to 0.85 [7].

To estimate the amount of production output needed to obtain a certain price level, we may rewrite (4) as

$$N = N_0 \times \left(\frac{C_N}{C_0}\right)^{\left(\frac{\ln 2}{\ln P}\right)} \tag{5}$$

where N=the required cumulative output to reach a cost level of C_N. Subscript "0" refers to data of a known time-point.

The dependence of the variables of (5) are shown in Fig. 2. For example with P=0.85, a 30% cost reduction requires a 4.6 x increase in the cumulative output; a 50% price drop 19.2 x.

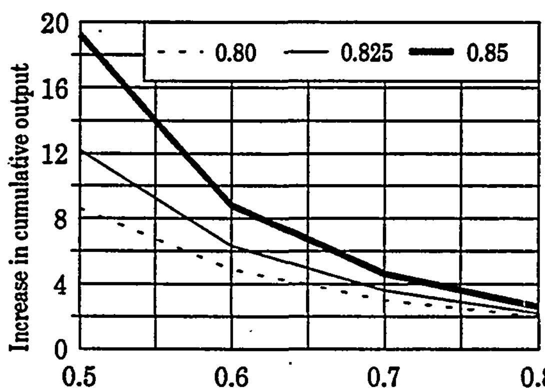

Fig. 2 Required product output increase versus reduction in unit-costs with progress ratio (P) as parameter (0.8-0.85).

2.3 MARKET SEGMENTS

We have divided the market for wind energy crudely into 3 segments shown in Table 1. At present most of the wind energy is within the early market which by nature is chaotic and by size small. When the price falls, the energy technology will move into larger segments. As the ultimate market, we consider the bulk power production where wind could at most reach a 15% share of the total production capacity. This limit is set by the intermittency of wind, but could be exceeded through the use of back-up power or energy storage.

The penetration of wind into market will consist of sequential diffusion steps with their own characteristic penetration parameters. We assume here that wind will move smoothly from one segment to another. Thus, one diffusion curve will be needed.

TABLE 1
MARKET SEGMENTATION OF WIND ENERGY

Segment:	Embryonic	Distributors	Raw power
Target group	demonstration introduction programs	distributing utilities private users	main utilities
Price target	wide range	3.5-5	2.5-3 ECU cents/kWh
Wind investment	1000-1100	700-800	500-600 ECU/kW
Segment size	<<1% of all electricity	1-2 % of total electricity	15% of total production

3 RESULTS

Denmark represents a good case for innovation diffusion of wind energy technology due to early entry of the country into the wind business as also due to the amount of several interactive companies in the field. Denmark dominates the global wind energy market as around every second wind mill originates from the country [8]. Based on ample production and cost data from Danish wind energy manufacturers, we were able to draw an approximate learing curve for Danish wind mills shown in Fig. 3.

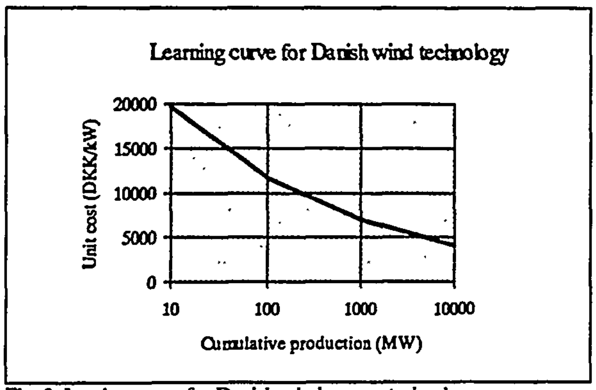

Fig. 3. Learing curve for Danish wind energy technology.

The progress ratio for the Danish wind technology was found to be approximately P=0.85 [9] which is well within the typical value range for manufacturing industries in general.

Followingly, we next consider the penetration of wind using emperical data for wind use. To determine the diffusion parameters for penetration in Europe, we consider three basic cases:

1. wind energy penetration follows strictly the present penetration pattern in the future [N, α, β variables]
2. wind energy follows present penetration pattern and reaches 4 GW in year 2000 [N_{2000}=4 GW; α, β variables]
3. wind energy penetrates smoothly throughout the years into the mass market with an upper limit of 100,000 MW. [N_{∞}=100,000 MW; α, β variables]

The diffusion model was fitted with above boundary conditions into wind capacity data for Europe (1981-94). The results are shown in Fig. 4.

The present trend (Fig. 4a, case 1) of the diffusion of wind energy in Europe indicates saturation at about 2.4 GW around year 2000 which may be a realistic figure for a demonstration market segment in general. Several public wind energy programs in Europe seem to force the market, however, to higher levels. Based on the estimates of EWEA [3], 4 GW in 2000 may be feasible which yields an upper limit of close to 5 GW around 2005 (Fig. 4b, case 2). This figure could also be considered as a limit for the introduction of wind energy in Europe. Assuming that wind energy would penetrate smoothly to the mass market (Fig. 4c, case 3) gives a 10 GW wind capacity in 2005 which from a industrial manufacturing point of view is still feasible. The saturation occurs now not until 2030.

One main difference in the cases shown above is in the penetration rate (α). A small market segment can be filled rapidly. For example in case 1 (Fig. 4a), the takeover-time ΔT defined in (3) is 10 years, whereas for the case 3 with a huge market segement ΔT=25 years. Also, it is worthwhile to notice that from the diffusion point of view, the market segments in case 1 and 2 may be a part of the mass market represented by case 3 (cf. multiple diffusion). The total size of the case 1 and 2 segments is 2.5% and 5% of the case 3 market, respectively. That is, if the present introduction of the wind energy continues to grow close to the saturation limits (2.5 and 5 GW), wind may already today be considered as the entry stage into the main market.

Based on the above observations, it follows that the performance of wind energy in the coming 5-10 years will be of outmost importance for the mass penetration. To analyze this case more in detail, we used the learning curve (Fig. 3) in parallel with the diffusion model to estimate possible cost reductions. We assume that half of all new wind production will be installed outside Europe. The market segment analysis (Table 1) indicated the following cost targets for wind technology:

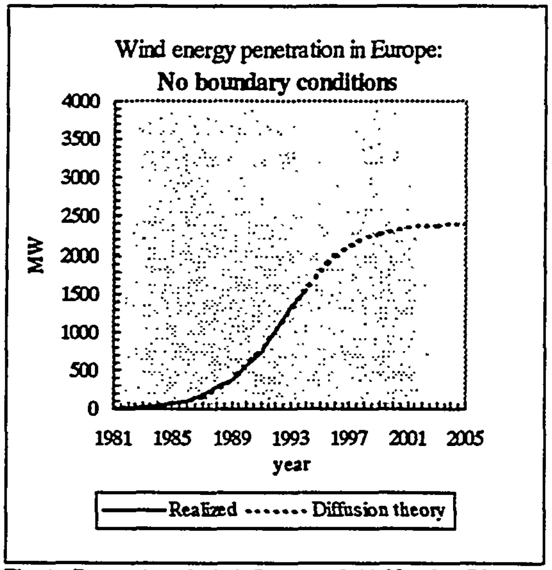

Fig. 4a. Penetration of wind. Case 1: α=0.46, N_{∞}=2,417 MW.

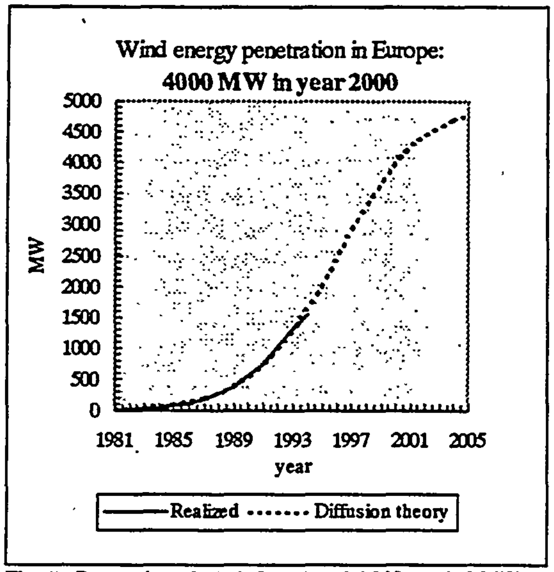

Fig. 4b. Penetration of wind. Case 2: α=0.35, N_{∞}=4,983 MW.

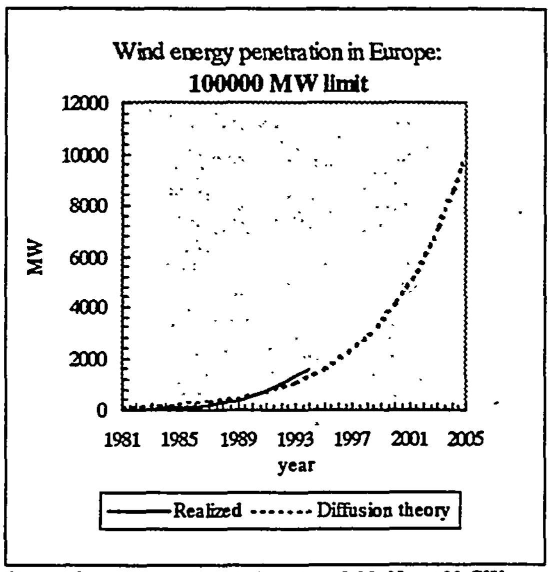

Fig. 4c. Penetration of wind. Case 3: α=0.20, N_{∞}=100 GW.

- a 30% cost reduction from present level to enter the electricity distribution market
- a 50% cost reduction from present level to enter the bulk power production

The learing curve for European/Danish wind technology is P=0.85 (Fig. 3) with a present cumulative output of about 2,500 MW. From Fig. 2 with these parameter values, we obtain the following production requirements for European industries:

- 30%: 11.5 GW cumulative production of which 5,750 MW installed in Europe
- 50%: 48 GW of which 24 GW in Europe

If these goals can timewise be optimally met then a smooth diffusion of technology will result.

The output volumes needed for a 30% cost reduction are within the upper limit for wind introduction in Europe and could be reached around year 2005. The industrial production volumes need to be increased up to 700 MW/yr. In the light of the mid-term goal of 4 GW in 2000 in Europe, a 30% cost reduction seems thus to be a realistic assumption.

If the technological development and progress of wind energy could be accelerated, e.g. through continued EU and national programs or improved branch cooperation, the progress ratio could theoretically still be improved. For example, with P=0.80 which is feasible in manufacturing industries [7], the volume needed drops to 7,500 MW of which 3,750 MW in Europe. The 30% reduction target would be reached in year 2000.

On the other hand, if fuel externalities were charged even partially and hence the price of traditional energy sources would rise, the targets are reached sooner. For example, if an extra 0.5 ECUcents/kWh tax were laid on conventional energy, i.e. the price targets in Table 1 were increased by this amount, and would effectively have the same impact as P=0.80.

The 50% price reduction necessitates around a tenfold increase of wind energy in Europe, or, 4 x the volume of the 30% reduction requirement. Assuming that wind penetrates first to the electricity distribution market through the 30% price reduction, the volumes perceived in this market segment should be well enough to allow building of wind up to the volume level needed for the 50% price reduction. With this assumption, wind energy would follow the penetration pattern shown in Fig. 4c and the main breakthrough to the bulk power market would take place around year 2010. An average manufacturing capacity of 2,200 MW/yr over 20 years would be then needed, or, a fourfold increase from todays global production levels. From an industrial point of view, such levels would not cause any problems yet.

4 SCENARIOS

4.1. EUROPE

Based on the results obtained in the previous section, we have constructed a few example scenarios for wind energy in Europe. The starting point used is that wind energy is able to move forward from the present embryonic market segment.

Three cases are presented in Fig. 5 with different saturation levels for wind energy. A 5% share of the total electricity production capacity in Europe represents a case in which wind will remain mainly as a supplementary energy source used by distribution utilities, or, by small local electricity producers. For comparison, the present situation of wind energy in Denmark, where 3.5% of the total electricity consumption is satisfied with wind power, would correspond closely to this case. The 10% and 15% levels describe wind energy as a source for raw electricity in Europe.

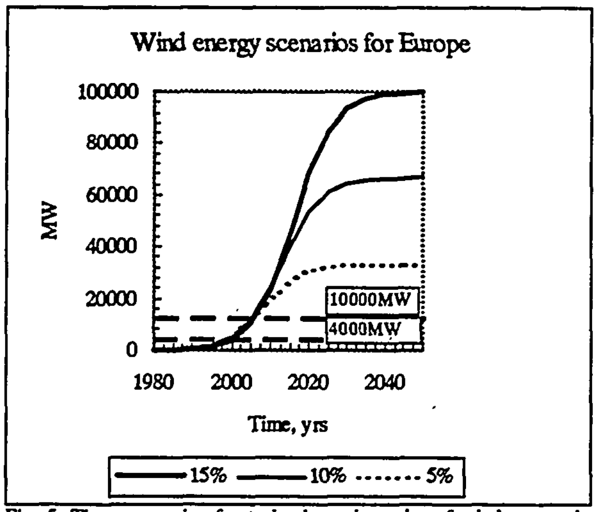

Fig. 5. Three scenarios for technology dynamics of wind energy in Europe. α=0.20, saturation level N_∞= total electricity capacity in Europe x maximum percentage of wind (5-15%).

The penetration rate for all cases is about α =0.2 which yields a take-over time of 22 years. For comparison, global nuclear energy has α=0.28 (Δ T=15.7 yrs) [2]. Thus, the magnitude of the penetration rate of wind energy may be considered realistic. The scenarios also show that the main growth stage of wind in Europe would occur after year 2010.

4.2 IMPLEMENTATION IN FINLAND

Finland is one of the least densily populated countries of the European Union with a good wind energy resource potential. Figure 6 shows mean wind speeds in Finland as also estimates for wind utilization. The latter figures also consider restrictions of land use. The total consumption of electricity in Finland is 65 TWh/yr .

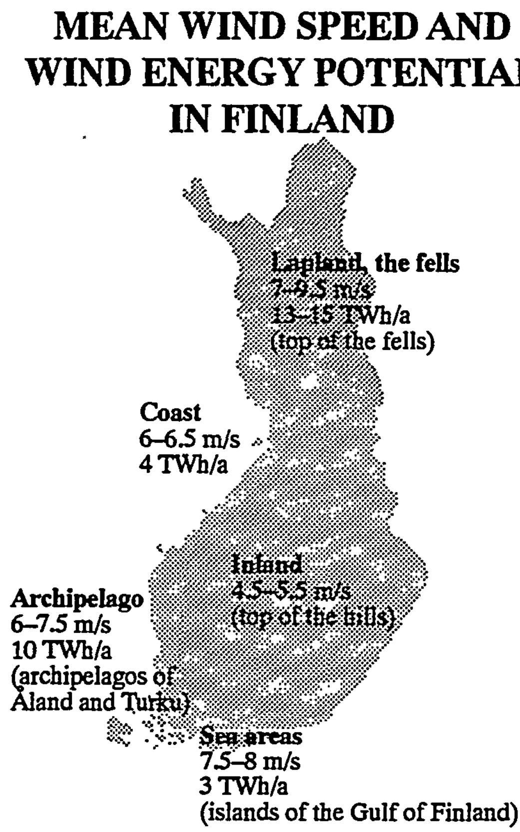

Fig. 6. Wind energy resources and potential in Finland.

In 1995, the total wind energy capacity will reach 6 MW. The Ministry of Trade and Industry launched in 1993 a wind energy introduction programme with a 100 MW target in 2005. Moreover, the Technology Development Centre financies wind R&D through the Advanced Energy Systems and Technologies Programme (NEMO2). The technology development in Finland mainly focusses on technology for complex terrain conditions, e.g. for arctic wind, where the cost of wind energy could be brought to the level of bulk electricity. The 100 MW programme helps to capture the major technology improvements done in the NEMO2 programme. An estimate of the realization is shown in Fig. 7.

Taking into account the whole electricity production system, a maximum of 4-5 GW ($=N_\infty$) wind could theoretically be integrated into the grid. When wind exceeds 1-1.5 GW, additional reserve back-up capacity would be needed to compensate for the intermittency of wind. For example, with 5 GW wind the need for new fast regulation power is 1.5 GW.

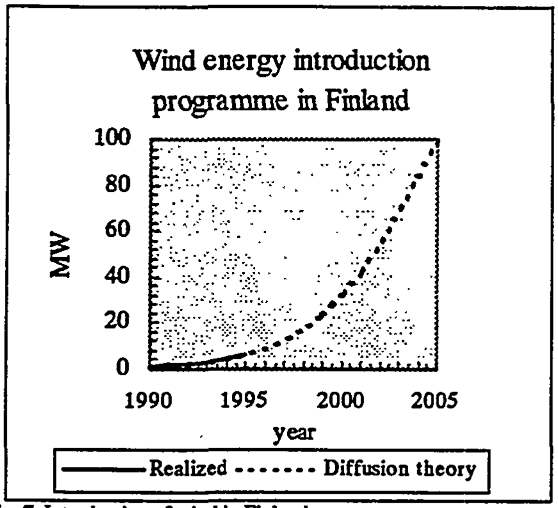

Fig. 7. Introduction of wind in Finland.

A set of scenarios is shown in Fig. 8 covering most of the likely futures. The present trend is described by the lowest penetration with a saturation level of 175 MW. This corresponds approximately to the maximum of wind introduction in Finland. The two fastest growing cases (N_{2010}=1 and 3 GW) are very unlike and their penetration rates exceed any of wind so far. To be realized, a major policitical decision would be needed. These two cases could still have timewise an influence on the European wind technology cost reduction through the learing curve, or in the range of 5%-15%.

The two remaining cases (N_{2020}=1 and 3 GW) are from the diffusion point of view the most feasible (α=0.17 and 0.28, respectively) and indicate a major entry of wind into the Finnish market from year 2010 onwards. These two scenarios have in practice no influence on technology cost reductions anymore.

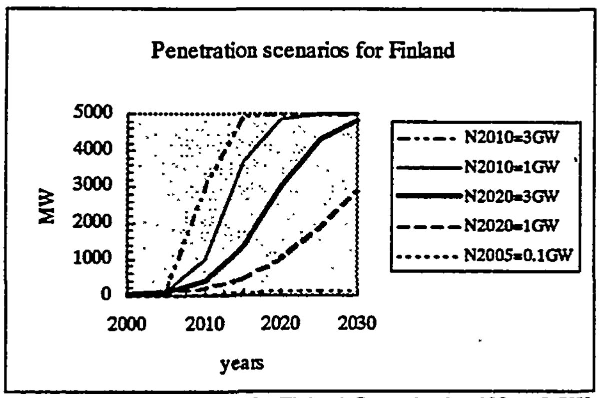

Fig. 8. Penetration scenarios for Finland. Saturation level N_{∞} =5 GW.

5 CONCLUSIONS

With a combined technology and diffusion model, we have studied market penetration of wind energy in Europe. The analyses made show that a major market break-through could be expected around year 2010. The present construction rates and trends of wind energy may achieve cost reductions of the order of 30% compared to the present level. A straight-forward moving into the bulk power market is unlikely and a penetration into some kind of intermediate market (e.g. electricity distributors) may be necessary.

It was also shown that the price and penetration of wind energy can still be influenced by technology development and market incentives. Even minor changes in technology learning and in energy prices could have a major effect on the penetration of wind energy.

For a small country like Finland, most of the wind energy capacity will be constructed in a business-as-usal case after year 2010 following the general global development. The influence of wind in the energy balance would be seen from 2020 onwards. If a major agressive wind program were launched before year 2000, it could still have an important influence on the wind energy technology and its price reductions.

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McCabe Wind Energy System

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ABSTRACT: A wind machine utilizing novel low-speed air foils and shrouds has been developed and is now undergoing a refinement process. Energy generated by the machine at a variety of wind speeds is significant. Use of the machine to compress air, which can serve a variety of applications, simplifies the total power producing system making it economical and practical for use at a variety of locations to fill many energy requirements.

1 INTRODUCTION

The McCabe Wind Energy System introduces a new airfoil design, which is a departure from aircraft wing or fan-shaped blades and is derived from air dampers used for air/fire/smoke control systems in large buildings, has produced a shape which is very efficient in a variety of wind velocities. This airfoil, in combination with appropriate shrouding, results in a wind machine which generates a significant amount of energy for its size.

The shroud design increases the dynamic pressure of air presented to the blade section and reduces back pressure on the exiting air. The net result is a significant gain in energy. The overall shape of the shroud is also designed to pivot the machine to face into the wind, so the system is not limited by wind direction.

Preliminary results indicate that the airfoil design and blade relationships result in a decrease in torque as wind velocity increases, preventing a significant or disasterous increase in the rotational rate of the wind machine. The system is shown to be self limiting in rotational speed. Greater energy can be extracted in varying wind speeds by switching automatically to larger or smaller power generators as wind velocity changes.

By utilizing this machine to compress air, rather than for the direct generation of electricity, a variety of energy needs can be met while eliminating problems associated with expensive equipment and the need to tie into an electric power grid. The storage of compressed air has little energy loss and is environmentally friendly.

Compressed air can be used directly to power a variety of tools and machines, or indirectly to pump water to an elevated reservoir or to power an electric generator. The heat of compression and cooling from expansion can be partially captured for a variety of applications while adding to the efficiency of the total system.

Collaborative testing is underway both in Doylestown, Pennsylvania, USA, and Galway, Ireland. System refinements and final designs are expected to be completed by the end of 1996. Limited production may begin within that period, and will be expanded as the final system specifications are established. E.U. support for field testing is being sought. The McCabe Wind Energy System has a US patent pending.

2 AIR FOIL DESIGN

In order to extract energy from relatively low wind velocities, airfoil designed by Francis McCabe which are utilized to control air flow in ducts in large buildings have been modified. Those earlier designs utilize lift to enhance damper opening and

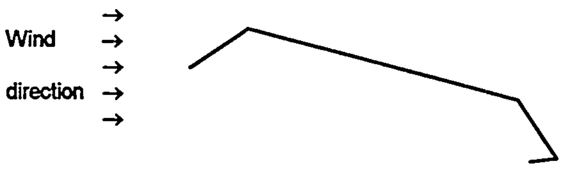

Fig. 1. Airfoil cross section. Significant lift can be generated at relatively low wind speeds, while simplicity of the shape makes fabrication a straightforward process.

thus air passage even at low airflow velocities, while still permitting a seal with the damper closed (US Patents 3,204,548 and 4,655,122).

Because there is no requirement to restrict air passage through this wind generator, these foils are modified to maximize low speed lift and energy extraction at a fixed blade angle optimal for average wind velocities, and can extract a significant amount of energy in wind speeds as low as 16 kilometers per hour. The unique blade cross section (Fig 1) can be produced from relatively light weight material such as aluminum. The blade shape has no twist, and because the material is of constant thickness both from root to tip and from leading to trailing edge, blade fabrication is relatively straightforward and inexpensive to produce in large quantities once tooling is established.

The lift generated by this airfoil has been measured in a low speed wind tunnel and compared to other designs. Of the various shapes tested using comparable surface areas, preliminary data suggests that this design generates lift which is approximately 2.4 times greater than that created by a conventional airfoil at a wind speed of 27 kilometers per hour, and 1.7 times greater at 40 km/hr. Additional tests with vertical sides mounted on the airfoils, simulating a shroud, resulted in the McCabe airfoil showing even greater comparable lift. Additional testing will follow (Section 7 below).

Blade lift and force generated from wind impact are two of several variables in the design of an efficient wind machine, which is also dependent on other factors. Initial tests with this system show that blade interaction is significant, with one blade enhancing the lift of another adjacent blade, and thus blade spacing is important.

The optimum blade angle depends in part on the average wind speed, and on the portion of energy created by lift versus impact force. Our functional prototype contains 14 blades radiating from a central hub with an axial incidence of 40°, resulting in an average angle of attack of 33° to the relative wind, which we have found close to optimal for wind velocities between 15 and 40 km/hr. Lift and blade interaction, as well as impact, are the sources of energy production.

Because the relative wind angle between the blades is effectively reduced as wind velocity increases, the system decreases in torque which limits rotational rate. The blades effectively become geometrically flat relative to the wind at high speeds. Thus a finite force limit is reached, virtually eliminating the likelihood of machine destruction due to overspeed in very high winds. Rotational rate is estimated to be 100 revolutions per minute at a wind velocity of 100 km/hr. Fewer blades with more spacing would reduce this desired effect, while blades spaced too closely result in an air dam.

3 SHROUD AND SUPPORT DESIGN

Housing for the horizontal wind machine has been designed to maximize energy production. The overall shape acts as a venturi, where entering air is accelerated in a cone shaped section, the blades are housed in a fixed diameter mid section, and exiting air is expanded in a reversed conical section with a trailing symmetrical shroud to straighten exiting air (Fig 2). A nose cone also contributes to the design efficiency.

The entire shroud is attached to the blade section and rotates as a single unit, aiding in maintaining momentum once rotation is established. Blade stability, rigidity and durability are also augmented by this design.

The conical intake section of the shroud funnels air into the rotational portion containing the airfoils, increasing dynamic pressure and speed of the incoming air for blade presentation. A cylindrical housing in the center of the assembly surrounds the airfoils, preventing energy from being lost through air exhausting outboard from the blades.

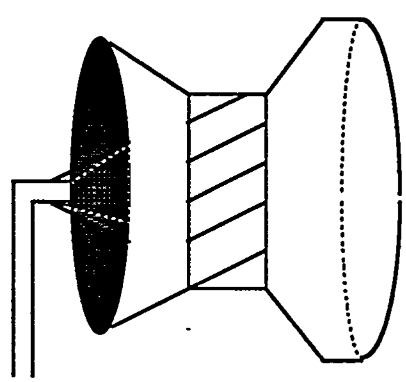

Fig. 2. Sketch of shroud assembly, nose cone, blades in the rotational center portion, and pivoting mounting pole containing internal power takeoff drive.

The exhaust section expands outgoing air, reducing back pressure on the blades to aid in extracting maximum wind energy, while the trailing cylindrical section assists with this process and helps induce air through the machine. Because the exhaust shroud portion is larger than the intake, it also steers the machine towards the prevailing wind direction.

A nose cone is mounted forward of the hub of the machine, in the interior of the intake and ahead of the blades. That cone diverts air outward towards the most efficient span section of the airfoils, and streamlines the rotational hub to reduce drag. Further testing will be conducted to determine the optimal diameter of the cone, i.e.: efficiency of the inner portion of the blades compared to diverting more air towards the outer section.

The total assembly is mounted atop a vertical pole, consisting of a rigid outer tube housing attached to the support structure, a free turning internal pipe which allows the assembly to pivot into the wind, and a central reciprocating shaft driven by the machine for transmission of the generated energy. An air compressor can be mounted in the base of the support structure or aft of the shroud. If applications require the direct production of energy in forms other than compressed air, a power takeoff can be substituted to drive a water or hydraulic pump, or an electric generator.

4 FABRICATION AND ASSEMBLY

Blade and shroud components are fabricated from 12 gauge aluminum, using relatively straightforward tooling. The rotational hub and support structure use steel piping, thrust and support bearings, and other off the shelf components.

The design results in a relatively low cost for parts fabrication and assembly, making it feasible to establish local plants for wind machine construction close to the location of intended use. Inexpensive plant setup, tooling, and operational costs should make it practical to establish such a facility for the production of a few hundred systems in a variety of locations, and compressed air generated by one or more McCabe wind energy units can provide a significant portion of the power required for manufacturing operations.

Because no external power is required to start the wind machine, as is the case with some vertical axis turbines, and no brake is needed to protect against overspeed, manufacturing and maintenance costs are kept to a minimum. Electricity is not required for any of the system operations, although a combination of electric or closed loop hydraulic power generation coupled with compressed air power has advantages for certain applications.

5 AIR COMPRESSION FOR ENERGY

Rather than use the McCabe wind machine for the direct generation of electricity, this design utilizes the converted wind energy to drive an air compressing system. A cylinder which compresses on both the up and down stroke of the piston is incorporated below the wind machine mount, and banks of such pistons can be added. Greater energy is thus produced with each revolution of the machine, and loads are more evenly distributed throughout the rotational cycle.

Compressed air can be generated at any wind machine/piston speed and permits a choice of producing high volume at lower pressures, or the converse depending on needs. Air storage tanks can be buried underground or placed atop buildings if desired for conservation of space and aesthetic purposes, and do not require co-location with the wind machine.

Systems designed for the direct generation of electricity are costly and complex, particularly if they feed a major energy network, and require additional equipment to convert electricity to a form compatible with the grid in frequency and voltage. Assuming minimal leakage, compressed air storage suffers little loss of potential energy over time, unlike the storage of electricity.

Transmission of compressed air by pipe has very little energy loss due to the low viscosity of air, and loss due to leakage is generally much less than in a water distribution system. Water traps or separators can be added to prevent the accumulation of liquid in the storage/transportation network, thus minimizing rust. corrosion, and danger of system blockage or damage due to freezing.

Compressed air can meet a number of energy requirements directly or indirectly. LevrAir's factory in Doylestown, Pennsylvania, uses air to power a variety of hand tools such as drills, rivet guns, wrenches and pneumatic hammers. Air is also used to power larger floor mounted systems such as presses, sheers and metal forming machines.

Compressed air can also act as an intermediate power source for electric generators. The advantage of this compared to direct wind machine energy for generator power results from a relatively constant, controllable energy source (air pressure and mass volume from a storage tank), rather than from variables caused by changes in wind speed and wind machine rpm which requires a voltage and frequency regulating system and/or an inverter. Similarly, compressed air can be used to drive water pumps or other hydraulic systems either at the wind machine site, or at remote locations since there is minimal energy loss during the transmission of compressed air.

6 THERMODYNAMIC CONSIDERATIONS

Heat energy, a byproduct of air compression and expansion, can be partially recovered and utilized not only for desired needs, but also to increase the efficiency of the air power system, unlike the unrecoverable loss experienced with the generation and transmission of electricity. Thermodynamic and gas laws are well known, as are the applications of heat pumps/heat exchangers.

Isothermal air compression and storage is the ideal method. With the incorporation of the isothermal heat exchanger to remove a portion of that induced heat, a greater net quantity of air can be stored in a tank of fixed size. The product of the exchanger (warm air or fluid) can then be used if desired, or discarded through a radiator.

Similarly, the temperature drop resulting from air expansion during exit from the storage system through a pressure regulator causes a decrease in the absolute air quantity available to power equipment and machinery. Again, if a heat exchanger is utilized to warm the expanding air, the cooled medium in the exchanger can be used for any desired need, simultaneously increasing the net work generated by the compressed air.

As an alternative, a closed loop heat exchanging system could be employed at locations where the air compressor and the equipment utilizing that air are in proximity to each other. The exchanger would extract heat from the compression and storage areas, and give that heat up at the compressed air expansion points, actions which would enhance the efficiency of the total system.

Although the initial equipment costs for such a thermodynamic system may be significant, once in place the heating/cooling system generates "free" energy while increasing the efficiency of compressed air storage and of power applications.

A number of uses for such thermodynamic energy have been proposed. such as heating buildings, greenhouses, and water. Cooling can be used for air conditioning buildings, sleeping accommodations in closed insect proof tents and for food refrigeration for example. A variety of such applications can either substitute for electric energy consumption, or be utilized in locations where electricity is unavailable.

7 CURRENT AND FUTURE TESTING

The first operational test wind machine is situated on the roof of a factory, and utilizes a 14 blade configuration with a diameter of 2.5m. Tests at various blade angles of attack have demonstrated that 33° with respect to the relative wind is the most efficient for modest wind speeds (15 to 40 km/hr). The machine is utilized to drive a piston type air compressor mounted vertically at the base of the supporting structure.

With the above system connected to piping and an air storage tank with a total capacity of 3,200 liters, this machine raised tank pressure at a rate of approximately 7 kiloPascals every five minutes. Using a system with a capacity of 260 liters, a maximum pressure of 275 kPa with wind speeds averaging 22 km/hr, and 620 kPa in winds of 40 km/hr were achieved.

One feature being explored is the possibility of using compressed air from the wind machine as input to a conventional compressor powered by an electric motor. From this, a significant reduction in electric power consumption needed to generate a given amount of air pressure in a storage tank could occur.

Initial experiments at the Levr/Air, Inc. factory in Pennsylvania have validated the basic design of the system, utilizing a 2.5 meter blade rotor diameter. Tests with the wind machine not attached to any power producing system demonstrated that rotation would begin at approximately 11 kilometers per hour of wind, and sustained at velocities as low as 5 km/hr. Loads can be applied after rotation is initiated, and tests of power and compressed air mass generated through an air compressor have begun.

A second test machine with a 2.5 meter blade diameter is being assembled at the Regional Technical College, Galway, Ireland (RTCG). Shroud lengths have been increased for comparative purposes to determine greatest efficiency. A variety of nose cone sizes will be utilized with the RTCG machine to determine optimize blade efficiency. Tests of the two machines will mirror each other, gathering quantified data which will correlate and compare power output as a function of total blade face area.

The time required to generate compressed air at various pressures in equal volume tanks will be measured at a variety of wind speeds and atmospheric conditions. The RTCG machine will be instrumented to monitor torque output, pressure drop across the turbine, and rotational velocity. Data on ambient wind speeds and conditions will be recorded simultaneously.

Further wind tunnel tests will be conducted to determine blade lift and drag characteristics at various wind speeds and angles of attack, and to measure lift versus impact contributions to total energy output. A computer model will then be constructed to match the variable machine characteristics to specific energy requirements and average wind conditions for potential users of the system.

Testing will also be done to demonstrate the structural integrity of the system at high wind velocities, and to measure the durability of various components. From that data, more detailed costs for system construction and maintenance will be generated.

While one year has been allocated for this additional test work and system refinement, production could begin in the interim based on the initial data which has been generated, the apparent efficiency and cost effectiveness shown to date, and to satisfy critical needs. A follow-on paper will discuss specific and more technical results.

8 SYSTEM COST AND EFFICIENCY

A manufacturing facility in Doylestown, Pennsylvania, USA, has costed the production of 3 meter diameter wind machines at less than US$4,000, including the mounting assembly and air compressor. The support platform, storage and transmission components, and other types of energy generators, are not considered because they must be customized to meet site and user-specific needs.

Assuming production occurs in regional facilities, shipping expenses are minimized although construction materials may have to be imported. System maintenance should also be modest, since only periodic lubrication is required. The need for replacement of parts due to wear and usage should also be minimal due to component simplicity. For example, blade durability and longevity is enhanced because of structural support at each end (hub and shroud).

Comparisons between this system and other existing wind energy machines is impossible to quantify at this stage, in part because compressed air is generated as the initial energy product rather than electricity. It is estimated that the 2.5m diameter machine produces the equivalent of 2 to 3 kilowatts. The goal is to achieve a unit cost per kilowatt of capacity of no more than US$1,000 for machines up to 5kw, and as low as $750/kw with larger systems.

The rise in material and manufacturing costs increases at a ratio significantly less than 1:1 as machine size and power capability is increased. A growth of about 70% in frontal area is realized when blade diameter is increased from 2.5 to 3m.

The product of lower energy loss during the storage and transmission of compressed air results in an advantage over electric energy systems requiring banks of batteries for local storage, and transmission where energy leakage occurs. Application costs are a one time event, be they purchase of machines and tools which operate from compressed air, or a thermodynamic system. Pneumatic tools are no more expensive than their electric counterparts, and have at least comparable useful lives.

As with any wind energy system, there may be a need for a backup energy source in areas where wind velocity is erratic. However, because the cost of compressed air storage tanks is modest and have a longer useful life compared to electric batteries, total storage capacity can more economically be modified as needed to meet the extremes of local wind conditions and power requirements. The possibility of using this system to pump water to high elevation reservoirs, as a means of storing potential energy, also exists.

The ability to generate significant energy at relatively low wind speeds results in the practicality of installation of this system in geographical areas where average wind velocities may be below those which are needed for other designs to be productive. Because the system can provide energy for local requirements without the need for connection or interface with a power grid, it becomes practical as a partial substitute for the electric energy requirements of small farms, rural villages, and isolated manufacturing facilities, particularly where the cost of importing electricity is high, and where it is impractical to generate electric power locally.

9 ENVIRONMENTAL IMPACT

Due of the need to locate any type of wind energy generator in an open area, shielding or disguising them from view is difficult and they occupy a given amount of land area. Because the McCabe wind machine operates at relatively low wind velocities, support towers do not need to be as tall as many other systems require, and do not need anchorage with guy wires. It is therefore practical to locate them in agricultural fields or atop buildings to minimize land area occupancy.

A second environmental advantage of the system is derived from the ability to bury air storage tanks and transmission pipes. Again this conserves space, and makes the system more aesthetically acceptable. Once the system is deemed air tight, with little or no leakage, access for maintenance is not required assuming that materials used are not subject to rust or other degrading factors.

Problems from electromagnetic field interference do not exist with a compressed air system, nor is there any net heat energy added to the environment since compression and expansion temperature changes are virtually equal. The danger of electric shock is also eliminated, although a burst compressed air line could be a physical hazard. In general, compressed air tools and machines pose slightly less of a safety hazard than do their electric powered counterparts.

10 CONCLUSION

The McCabe Wind Energy System offers a new type of wind machine and associated compressed air energy system which have been designed to fill a number of power requirements at a comparatively low cost. Productive power can be generated at relatively low wind speeds, making energy available for locations where other sources are either expensive or unavailable. The use of compressed air can substitute for several energy applications which currently rely on electricity.

While system refinements are ongoing, the initial testing indicates that the basic design is efficient and effective. It is hoped that this developmental work will lead to E.U. support for further field tests and demonstration projects.

The desire is to license local manufacturers to produce these systems in various regions where they will be utilized, reducing shipping costs and logistics, and providing a maintenance support base close to the users. Local fabrication can contribute to regional economies through employment and the creation of manufacturing facilities which can be utilized for other purposes as well.

ACKNOWLEDGMENT

The cooperation of the Regional Technical College, Galway and support from the Irish government are greatly appreciated, and will help expedite the implementation of this system.

A number of individuals have contributed their time and talents to the developmental process, and rather than listing them individually with the risk of omission, we thank them all.

15.8.1995
Juhani Mäkinen

LID-3000

ICE DETECTION AND DEICING SYSTEM IMPROVES THE ECONOMICS OF A WIND TURBINE IN THE ARCTIC WEATHER CONDITIONS

The Finnish Lapland is an exellent test area for the wind turbines due to strong winds and heavy icing. Also the need of ice protection is evident, for wind turbines cannot be used in the area at all without such devices which keep the blades free of ice, rime frost or heavy snow.

Labko Ice Detection Oy has been working in good cooperation with VTT and Kemijoki Oy to solve this problem technically and economically by developing an ice detector and deicing system. This system detects ice when its thickness is 0,5 mm and melts it so that the blades will stay clean during the ice accretion. The enclosed estimation process indicates that the investment in this system is economically profitable.

1. THE ICING DAYS AND THE LOSS OF ENERGY IN THE FINNISH LAPLAND

The rime frost, ice or heavy snow accretion period starts in October and ends in May (Sodankylä Pyhätunturi area, altitude 500 m). According to the studies the rime formation can be so fast that the turbine must be stopped in few hours. The blades will stay in rime frost, ice or snow as long as the first thaw weather comes and blades will melt naturally. This process will be repeated again and again by the end of May. It seems that in February the turbine stands the whole month.

In this paper the production loss has been calculated summarizing the actual average wind and the elapsed time or elapsed aerodynamic efficiency during the first two icing days. The calculated production losses are for

	200 kW turbine	290 mWh	17 400 USD
and			
	500 kW turbine	724 mWh	43 440 USD

2. THE INVESTMENT COST OF ICE DETECTION AND DEICING SYSTEM

In this exampel the investment has been allocated for 4 wind turbines. The investment includes one ice detector installed in the blade tip of one turbine, one meteorological ice detector, which is located in the ground. This additional detector is a backup equipment for the blade detector. The leading edges of the blades have heating elements controlled by tyristors and a control unit in each turbine. The control signals have been transmitted by radio modems in order to avoid the expensive wiring in the park. Also the cost of the extra lamination, feed through element and slide rings have been estimated in the investment cost.

The estimated investment costs are for 4 (four)

	200 kW turbines	67 000 USD
and		
	500 kW turbines	114 400 USD

3. THE COST OF THE HEATING ENERGY

The power consumed for the melting the ice covering the leading edge is very sensitive for the shape of the heating elements and zones. Also the airflow after melting (laminar or turbulent) affects 2-3 times to the needed power.

In this calculation the heating energy has been used 24 hours when rime accretion is taking place and the annual total consumption is for one (1)

	200 kW turbine	33,1 mWh	1 980 USD
and			
	500 kW turbine	93,0 mWh	5 580 USD

4. THE PROFITABILITY OF THE INVESTMENT

The total cost of the investment and the energy consumed is for 4 turbines of

	200 kW	75 610 USD
and		
	500 kw	136 720 USD.

The total annual savings are for 4 turbines of

	200 kW	69 600 USD
and		
	500 kW	173 760 USD

The profitability of the investment of four (4) turbines in these cases can be presented in the form of pay-back time (T). which will be

	200 kW	T= 75 610/69 600=1,09 year
and		
	500 kW	T=136 720/173 760=0,79 year

5. SUMMARY

The profitability of the LID-3000 ice detection and deicing system in the wind mill park including 4 or more turbines will be good when measured in pay-back time. Even smaller turbines (200 kW) can benefit this type of investment.

The calculation made includes several safety aspects so that results are also safe from the

Technically it is important that the ice detector is located in the blade tip and gives so early ice warning that the blade surface remains clean for two reasons:

1. The aerodynamic torque is highest possible and

2. The airflow around the icing area of the blade is laminar for lower heating energy consumption.

In the regions where the icing conditions are not as serious as in the example the icing causes however the similar production losses. Even thinner layers of ice, which do not stop the turbine, will cause production losses (25-50%). In these cases the above investment will be profitable but with longer pay-back time.

A Neuro-Fuzzy Controlling Algorithm for Wind Turbine

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ABSTRACT--The wind turbine control system is stochastic and nonlinear, offering a demanding field for different control methods. An improved and efficient controller will have great impact on the cost-effectiveness of the technology. In this paper, we discuss a design method for a self-organizing fuzzy controller, which combines two popular computational intelligence techniques, neural networks and fuzzy logic. Based on acquisited dynamic parameters of the wind, it can effectively predict wind changes in speed and direction. Maximum power can always be extracted from the kinetic energy of the wind. Based on the stimulating experiments applying nonlinear dynamics to a "Variable Speed Fixed Angle" wind turbine, we demonstrate that the proposed control model and learning algorithm provide a predictable, stable and accurate performance. The robustness of the controller to system parameter variations and measurement disturbances is also discussed.

1 INTRODUCTION

Wind turbine is one main component of a wind energy system (WES). The wind fluctuation is stochastic, as is the power demand on the output node. The power train (turbine-generator-converter) is highly nonlinear. Moreover different wind-turbine configurations pose a variety of design goals. The wind-turbine control is an application area with an interesting set of problems for the control engineers. These problems have not been adequately solved and continue to pose challenges to the control community. There is no general methodology available for the design of controllers for such highly nonlinear dynamical systems as the wind turbine represents. Recently, this has motivated the application of intelligent, adaptive control strategies based on neural computing and fuzzy logic [1]-[3].

The emergence of artificial neural networks as an alternative for traditional computing techniques has resulted in a wide variety of applications, *e.g. function approximation, pattern classification, control applications, etc.* The learning and generalization abilities make neural networks better candidates for control applications by providing disturbance reduction and addaptivity. Due to the highly parallel computing nature, neural networks are able to interpret and process large amounts of sensory information, which traditional control systems are unable to handle. In addition, very little *a priori* information about the system dynamics is necessary for the design of such controllers [4],[5].

Fuzzy logic, introduced by L.A. Zadeh in the 1960's, is close to the spirit of human thinking. Its main idea is to simulate human thinking and reasoning according to a mathematical framework. During the last years, fuzzy control has emerged as one of the most active and fruitful application areas of fuzzy logic [6]-[8].

However, the operations of neural networks have also some weaknesses. For example, in the popular MLP (multilayer perceptron) network, the knowledge of the system is distributed into the whole network as synaptic weights. It is very hard to understand the meaning of weights in a learning process and the incorporation of prior knowledge into the system is usually impossible. Although the knowledge of the RBF (radial basis function) and the SOM (self-organizing map) is in a more suitable form, it cannot be easily extracted into linguistic rules. The integration of neural networks and fuzzy logic has given birth to a new research field callled neuro-fuzzy systems. These systems have the potential to capture the benefits of both fields into a single framework. That is, the operation of the system is expressed as linguistic fuzzy statements, the learning schemes of neural networks are used to train the system. Neuro-fuzzy controllers have been used successfully for a wide variety of processes [9],[10].

The main objective of this study is to provide a general control design method for the wind turbine and verify the effectiveness of the scheme. Section 2 deals with the overall control system. The FSOM (fuzzy self-organizing map) architecture and learning algorithm are discribed in Section 3. Section 4 presents the simulation results and Section 5 provides some conclusions.

2. CONTROL SCHEME

An effective wind-turbine control algorithm must reflect as well system dynamic characteristics as the anticipated working environment, namely the wind regime (speed, direction, and fluctuation). The control system should be considered in any analysis of cost effectiveness or dynamic behaviour of the whole WES. Various researchers have commented on the nonlinear relationship between wind spectrum, turbine torque and pitch angle. The dynamic behaviour of the turbine is highly dependent on wind speed. The power available from a WES is approximated as a cubic function of the wind velocity. The wind spectrum consists of both high-frequency gust and low-frequency mean wind-speed components. The modelling of the wind spectrum is most important. It is apparent that WES is a highly nonlinear dynamical MIMO (multipl inputs and multipl outputs) system. This fact along with the turbulent meteorological environment, renders that non-adaptive conventional PID (proportional-integral-derivative) controllers are inadequate.

By a detailed analysis of the properties of the WES, we find that the MIMO system can be divided into a SIMO (single input and multipl output) or further into a SISO (single input and single output) subsystem. Splitting the whole system into SISO models has the following advantages. (a) The behavior of SISO systems is well understood, hence controller design is easier than for MIMO system. (b) It is easy to choose seperate optimum values for each SISO network to get better convergence and tracking.

Our control objective is to track and extract maximum power from the WES, that is to ensure complete utilization of available wind energy under varying wind velocities.

The preliminary phase in the developement process is to design a SISO control system as shown in Fig. 1. In the subsequent phases, the designed models can be used as start-up controllers for further training of the combined scheme.

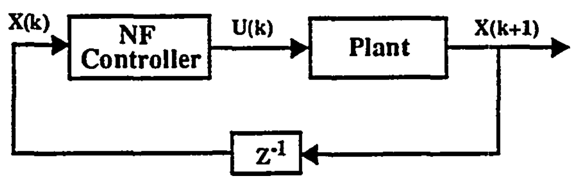

Fig. 1: SISO Control System

For a given state of the plant at time k, the neuro-fuzzy controller will generate an input to the plant, and the plant will evolve to the next state at time instant $k+1$. The individual controller is realized as a FSOM network.

3 SELF-ORGANIZING FUZZY CONTROLLER

3.1 FSOM ARCHITECTURE

The FSOM is a fuzzy version of Kohonen's SOM model [11]. The SOM is an unsupervised neural network, which without any supervisor signal creates spatially organized internal representations of various features of the input signals and their abstractions . It implements distance computation between input and reference codebook vectors [12]. The input signals $x = [x_1, x_2, \dots, x_n]$ are fed to all neurons, where they are multiplied by each neuron's connection weights $w_i = [w_{i1}, w_{i2}, \dots, w_{in}]$. Thus the output of each neuron y_i ($i = 1, 2, \dots, m$) is given by the formula:

$$y_i = \sum_{j=1}^{n} w_{ij} \, x_j \qquad (1)$$

The basic idea of the FSOM is to replace the weighted sum (1) of the neurons by fuzzy rules. The basic structure of the FSOM is illustrated in Fig. 2.

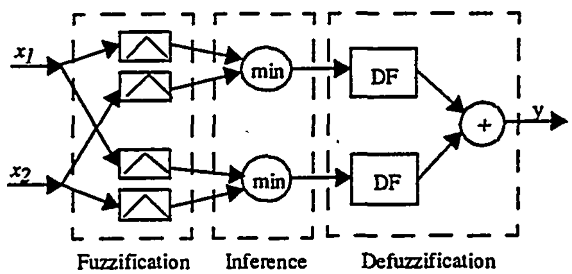

Fig. 2: The Basic Structure of FSOM

Fuzzy rules are the fundamental part of the knowledge base in a fuzzy inference system. They have the general *if-then* form:

if x_1 *is* U_{i1} **and** x_2 *is* U_{i2} **...and** x_n *is* U_{in} **then** y *is* a_i . . . (2)

where each condition (x_j *is* U_{ij}) is interpreted as the membership value $u_{U_{ij}}(x_j)$ of the input signal x_j in the fuzzy set U_{ij}. The consequence a_i of each rule is a singleton. The membership function used in this study is a triangular function, which is defined as

$$\begin{aligned} \mu_{U_{ij}}(x_j) &= (x_j - sl_{ij}) / (c_{ij} - sl_{ij}) \,, & sl_{ij} \le x_j \le c_{ij} \\ \mu_{U_{ij}}(x_j) &= (x_j - sr_{ij}) / (c_{ij} - sr_{ij}) \,, & c_{ij} \le x_j \le sr_{ij} \\ \mu_{U_{ij}}(x_j) &= 0, & \text{otherwise} \quad (3) \end{aligned}$$

where c_{ij} is the center of the fuzzy set U_{ij}. Variables sl_{ij}

and sr_{ij} are the left and right spreads of the fuzzy set U_{ij}, respectively. The fuzzy sets define a region in the input space, where the fuzzy rule fires.

The firing strength α_i of each fuzzy rule is calculated according to

$$\alpha_i = min\{\mu_{U_{i1}}(x_1), \mu_{U_{i2}}(x_2), \ldots, \mu_{U_{in}}(x_n)\} \quad (4)$$

After that, the outputs a_i of the rules are combined together by a weighted average according to

$$y^* = \left(\sum_{i=1}^{m} \alpha_i \cdot a_i\right) / \left(\sum_{i=1}^{m} \alpha_i\right) \quad (5)$$

where m is the number of rules.

Fig. 3 shows the operation of the FSOM.

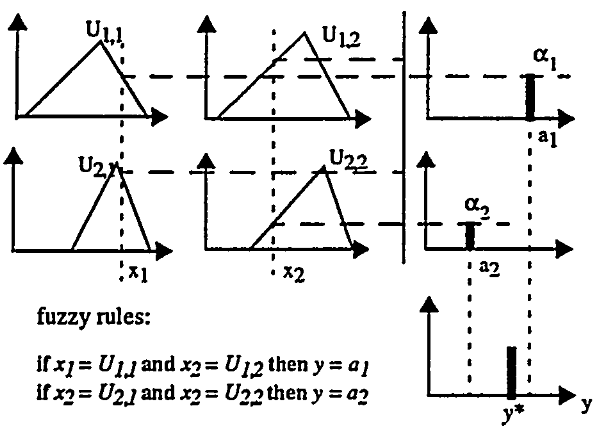

Fig. 3 The Operation of FSOM

3.2 LEARNING ALGORITHM

The learning of the neuro-fuzzy system can be divided into two main parts, structure identification and parameter identification. The former is related to finding a suitable number of fuzzy rules and a proper partitioning of the input and the output space. The latter deals with the adjustment of system parameters, such as membership functions and other possible parameters.

The FSOM learning method consists of three stages:

Stage 1. Slef-organization of the centers of the fuzzy rules.

First, the number of the fuzzy rules has to be determined. After that, the centers of the fuzzy rules are self-organized by the unsupervised SOM algorithm [12].

Stage 2. Forming of fuzzy sets.

The fuzzy sets are formed around the center vector c_i. The left and right spreads sl_i and sr_i respectively, are given a constant width w_0 according to

$$c_i - sl_i = sr_i - c_i = w_0 \quad (6)$$

Each rule is also labeled with a preliminary ouput value a_i. This is done by first feeding all the input samples x_k to the system and then collecting the resulting firing strenghts α_{ik}. After that, the preliminary output values a_i can be calculated according to

$$a_i = \frac{\sum_{k=1}^{l} \alpha_{ik} \cdot y_k}{\sum_{k=1}^{l} \alpha_{ik}} \quad (7)$$

where y_k ($k = 1,2,\ldots,l$) is the output of the data set.

Stage 3. Tuning of fuzzy sets.

The fuzzy sets are tuned by a modified LVQ (learning vector quantization) algorithm [13]. The algorithm is based upon the concept of a window which is simply defined as the overlapping area of the two most firing fuzzy rules.

When the input sample falls into the window, one spread of the first runner-up rule is chosen to be updated by moving the spread s_{rk} (sl_{rk} or sr_{rk}) either towards the center c_{wk} or the spread s_{wk} of the winner rule w.

The updating is done according to

$$s_{rk}(t+1) = \begin{cases} s_{rk}(t) + g_U(t)\,[c_{wk}(t) - s_{rk}(t)] & \\ \quad sgn\,(y - y^*) = sgn\,(a_r - a_w), & \\ s_{rk}(t) + g_U(t)\,[s_{wk}(t) - s_{rk}(t)] & \\ \quad otherwise & \end{cases} \quad (8)$$

where c_{wk}, c_{rk} are the centers and s_{wk}, s_{rk} are the spreads of winner rule w and first runner-up rule r, respectivly. The learning rate of fuzzy sets g_U is chosen so that $0 < g_U < 1$. The variable y is the desired output of the training data set, y^* is the actual output of the FSOM, a_w is the output of the winner rule, and a_r is the ouput of the first runner-up rule. This updating either increases or decreases the influence of the first runner-up rule in the output of the FSOM.

When the input sample falls outside the window, the centers and the outputs are updated according to

$$c_w(t+1) = c_w(t) + g_U(t) \cdot [x(t) - c_w(t)] \quad (9)$$

$$a_w(t+1) = a_w(t) + g_a(t) \cdot \alpha_w(t) \cdot [y - y^*] \quad (10)$$

where $g_a(t)$ is the learning rate of the singletons ($0 < g_a(t) < 1$) and $\alpha_w(t)$ is the firing strength of the winner rule.

4 SIMULATIONS

The proposed control scheme is general and it can be applied to a variety of control problems. We firstly apply it to the *Inverted Pendulum System* to demonstrate its effectiveness. Then we use it in the *Variable Speed Fixed Angle* wind turbine control system.

The inverted pendulum is a classic example of an inherently unstable system [10]. The state at time instant k is specified by four variables: the pole angle θ, the angular velocity θ', the horizontal position and the velocity of the chart. The dynamics of the pole can be defined as

$$\theta'' = \frac{g \cdot \sin\theta + \cos\theta \cdot \left[\frac{-F - ml\theta^2 \sin\theta}{m_c + m}\right]}{l \cdot \left[\frac{4}{3} - \frac{m\cos^2\theta}{m_c + m}\right]}, \qquad (11)$$

where $g=9.8\ m/s^2$ is the acceeration due to gravity, F is the force applied to the cart, $m_c = 1.0Kg$ is the mass of cart, $m = 0.1Kg$ is the mass of pendulum, and $l = 0.5m$ is the distance from the pivot to the pendulum center. The aim of the controller is to apply a force sequence such that the pendulum is balanced and the cart does not hit the edge of the track.

The nonlinear differential equation of the system is simulated by the linear approximation. The parameters of the controller are the centers, spreads, and outputs of the fuzzy rules plus the number of rules. The consequent parameters of a fuzzy rule are all set zero, premise parameters are set in such a way that the membership functions can cover the domain interval completely with sufficient overlapping of each other (since domain knowledge about the inverted pendulum system is not initially available). The training data set in each training epoch contains desired input-output pairs of the form: (*system state, desired trajectory*).

To achieve the control goal in a near-optimal manner, the objective training is to minimize the cost function

$$J = \sum_{k=2}^{K} \theta^2(k) + \lambda \sum_{k=0}^{K-2} u^2(k), \qquad (12)$$

where the coefficient λ accouts for the relative unit of control effort.

It shows that the performance of neuro-fuzzy controller is quite good and the control system can track the nonliear dynamic properties of the system. If the initial conditions or parameters of the system are changed, similar results are achieved. So the controller can survive substantial changes of plant parameters.

Next we apply the scheme to the *Variable Speed Fixed Angle* wind turbine control system in a WES.

The neuro-fuzzy controller unlike conventional ones does not require a detailed mathematical model of the actual process. However, an understanding of the system and the control requirements are neccesary. In our scheme, two real time measurements, namely the error $e = (P_d - P_o)$ and the rate of change e' of error, are used as the input signals of the controller. P_d is the desired ouput power of the WES at a given wind velocity and P_o is the actual output of the WES. The output of the controller is used to control the modulation index *Mi* of the static power convertor. By using the software simulation package MATLAB, the closed loop system responses to the variations of the wind speed have been studied.

The simulation results show that with increasing wind speed, the mechanical power input to the system increases. This causes the rotor to accelerate increasing the terminal voltage of the synchronous generator. This in turn increases the power output of the convertor and accordingly the power drawn from the whole WES, thereby ensuring complete utilization of the available wind energy. In addition, the controller can damp the fluctuation and noise in wind velocities.

5 CONCLUSIONS

In this paper, we propose a general control design scheme for nonlinear dynamical applications by using a neuro-fuzzy algorithm and demonstrate its effectiveness by the inverted pendulum system. The method is succesfully applied to the wind-turbine controller of a WES.

The neuro-fuzzy controller does not require a detailed mathematical model of the process, very little *a priori* information about the system dynamics is necessary for the design of such controllers. The modified LVQ learning algorithm for FSOM converges more fast than the gradient-descent one. It is shown that the scheme provides an effective on-line control strategy for the wind turbine, accordingly the scheme can track and extract maximum power from the kinetic energy of the wind. It can also stablize the system parameter variations and measurement disturbines. We hope the proposed control scheme will find wide applicability in control engineering.

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Directly driven generators for wind power applications

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ABSTRACT: The paper deals with an analysis of directly driven, low-speed wind generators. The generators studied were a permanent-magnet synchronous machine and an asynchronous machine. The machines were compared with a typical generator of a wind power plant. The electromagnetic optimisation of the machines was done by the finite element method. The rated power of the generators was 500 kW and the rotational speed was 40 rpm.

I. INTRODUCTION

The rotor of a typical wind turbine rotates at a speed of 20 – 100 rpm. In conventional wind power plants the generator is coupled to the turbine via a gear so that it can rotate at a speed of 1000 or 1500 rpm, Fig. 1. However, the gearbox brings weight, generates noise, demands regular maintenance and increases losses. In a directly driven, low-speed wind generator no gears are needed and these disadvantages can be avoided, Fig. 2.

Many types of directly driven wind generators have been designed [1]. The first commercial 500 kW generator was a synchronous machine excited by a traditional field winding. A 150 kW linear induction machine [2] and a 20 kW buried magnet synchronous machine [3] have been tested in laboratories. Some experimental machines in the power range of a few kilowatts have been built, e.g. a surface-magnet radial-flux machine [4], a toroidal axial-flux machine [5, 6], a double-stator axial-flux machine [7] and a transverse-flux machine [8]. Nowadays the greatest interest is in permanent-magnet generators for wind power plants, because the characteristics of permanent-magnet materials are improving and their prices are decreasing.

There are three contradictory demands in the construction of the generator. The cost and the weight should be low and the efficiency should be high. The efficiency can easily be increased by using more copper and magnet material, but then the price will soar. There may be a great number of poles in a low-speed generator and this increases the diameter of the rotor. Permanent magnet excitation allows the use of a smaller pole pitch than in conventional generators.

The aim of this study is to analyse a directly driven permanent-magnet wind generator and to compare it with an asynchronous generator.

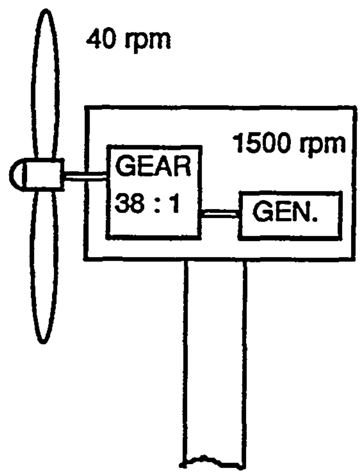

Fig. 1. Typical wind power plant.

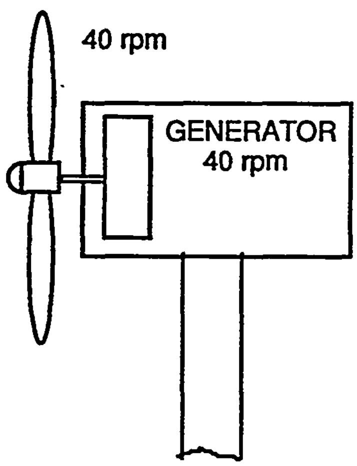

Fig. 2. Directly driven wind power plant.

II. DESIGN OF THE GENERATORS

A. Introduction to generators

A directly driven, low-speed permanent-magnet synchronous generator and an asynchronous generator were designed and compared with a typical wind generator. The designed generators were directly coupled to the wind turbine. The rated power of the generators was 500 kW and the rated rotational speed 40 rpm. However, there might be a great number of poles in such low-speed machines and the air-gap diameter would be large. The generators were designed to be used with a frequency converter in order to allow variable speed operation. The generators could be used for electrodynamic braking by connecting resistors and capacitors to the generator terminal.

The power of the generators was limited by temperature rises in the stator winding and in permanent magnets. The temperature rise depended on the power losses and the cooling of the machine. The stator winding had class F insulation, limiting the temperature rise to 115 °C. The temperature of the magnets was limited to be 60 °C.

The calculation of the operating characteristics of the generators was based on a time-stepping, finite element analysis of the magnetic field [9]. The field was assumed to be two-dimensional. The losses of the machines were calculated with a sinusoidal supply.

B. Permanent-magnet generators

A 500 kW directly driven permanent-magnet wind generator was designed. The simplest way to construct a rotor with a great number of poles was mounting the magnets onto the surface of the rotor yoke, Fig. 3. Therefore, it was necessary to use high-energy magnets such as NdFeB magnets to provide an acceptable flux density in the air gap. The remanence of the NdFeB permanent magnets used was B_r=1.14 T and the coercivity H_c=850 kA/m.

The frequency of the generator was 26.7 Hz. The machine had less iron losses than if it had been designed with the frequency of a 50 Hz. The number of poles was then 80 in this design.

Torque ripple and cogging torque cause noise and vibration in the machine. A fractional slot winding was chosen to make the torque ripple and cogging torque smaller than with integral slot winding. The number of slots per pole and phase was chosen to be 1.5, because then the rotor eddy current losses were small and the width of the stator teeth big enough. With the stator slot open, the cogging torque of the machine might be rather high. The width of the slot opening should be as small as possible. The slot opening may be at least half of the slot width if bar winding is used in the machine. The slot opening can be smaller when round wire winding is used. The diameter of the copper wire was 1.9 mm and the width of the slot opening was as small as possible, 3 mm. The round wire winding was also used to limit skin effect in the stator winding.

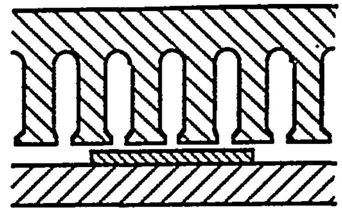

Fig. 3. Cross-sectional geometry of the surface-magnet machine.

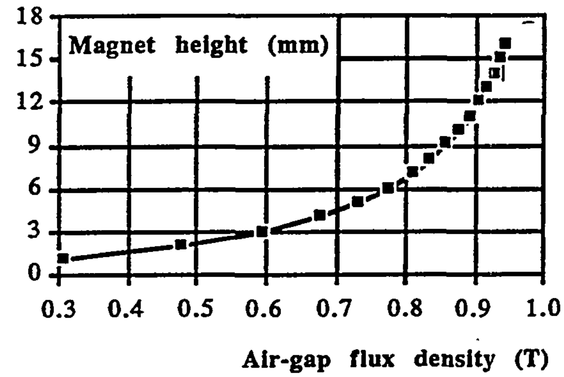

Fig. 4. Magnet height as a function of air-gap flux density for the designed generator.

The magnet height was directly proportional to the air-gap length. For practical reasons, the air-gap length should be at least 1/1000 of the air-gap diameter in a low-speed machine. It is difficult and expensive to manufacture a rigid enough construction for a small air-gap length. The necessary magnet height of the designed machine as a function of the peak air-gap flux density is shown in Fig 4. The air-gap flux density should not be too high for the permanent-magnet machine. Very much magnet material would have to be used if the peak air-gap flux density exceeded 0.8 T.

The air-gap torque was dependent on the magnet width. The magnet width affected also the voltage waveform and efficiency of the machine. When the width of the magnets was 0.6 – 0.8 times the pole pitch, the machine had a big air-gap torque and less losses [10].

The stator core segments were made of 0.5 mm laminations. The maximum flux densities were 0.8 T and 1.7 T in the air gap and stator tooth, respectively. The stator yoke was made much thicker than what was magnetically necessary in order to have a rigid structure. The stator winding was a three-phase, two-layer winding. The machine had 100 turns in series in each stator phase. The number of parallel paths was 2 and each stator slot had 4 coil sides.

The rotor yoke was a cylinder made of massive steel. The maximum flux density was below 1.2 T in the rotor yoke. The width of the magnets was chosen to be 2/3 times the pole pitch, because the losses were then small, air-gap torque high and the voltage also had an almost sinusoidal waveform. The main parameters of the generator are given in Table I.

TABLE I
MAIN PARAMETERS OF THE PM-GENERATOR

	PM (40)
Number of poles	80
Number of phases	3
Number of stator slots	360
Stator outer diameter [m]	2.7
Stator inner diameter [m]	2.5
Rotor inner diameter [m]	2.4
Air-gap length [mm]	2.5
Magnet's height [mm]	7
Core length [m]	0.5
Connection	star
Rated voltage [V]	590
Rated frequency [Hz]	26.7
Rated current [A]	490
Rated output power [kW]	500

The cooling of the machine was analysed by a thermal network [10]. Most of the losses were concentrated in the stator winding and the permanent magnets had very low losses. The stator had a relatively homogeneous temperature rise and the largest temperature gradient was between the stator core and cooling air. The temperature difference between the permanent magnets and air-gap flow was small, only 2 – 6 °C. The generator was chosen to be asymmetrically cooled with radial cooling ducts and a flow rate of 1 m^3/s. The generator had constant speed external ventilator, because it was operated at different speeds and powers. The temperature rise of the stator winding and magnets was 80 °C and 20 °C, respectively. The cooling method of the generator is shown in Fig. 5.

The efficiency of the variable speed machine at rotational speeds of 20 – 40 rpm is shown in Fig. 6. The speed was 40 rpm at the output power of over 200 kW and 20 – 40 rpm at the power of 25 – 200 kW. The efficiency at rated load was 95.4 %. The maximum air-gap torque was 2.4 times the rated air-gap torque.

C. Asynchronous generators

The advantages of an asynchronous machine include low maintenance costs, simplicity of structure and long life-cycle. A generator with a large air-gap diameter must have a rather large air gap for mechanical reasons. Because of the large air gap the magnetising current will be extremely high. Furthermore, the generator will operate with a small power factor.

First, calculations were made for a machine with the same frame size, stator winding, stator current density and air-gap length as in the permanent magnet machine designed. It was possible to get only 230 kW output power in the same stator current density as in the 500 kW permanent magnet machine designed. The losses of the machine could not be too high because the temperature of the machine would have increased too much. The power factor of this machine was 0.46 and the efficiency 87.2 % at rated load. The maximum air-gap torque was 2.3 times the rated air-gap torque.

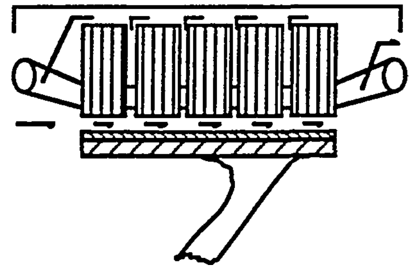

Fig. 5. Cooling method of the pm-generator.

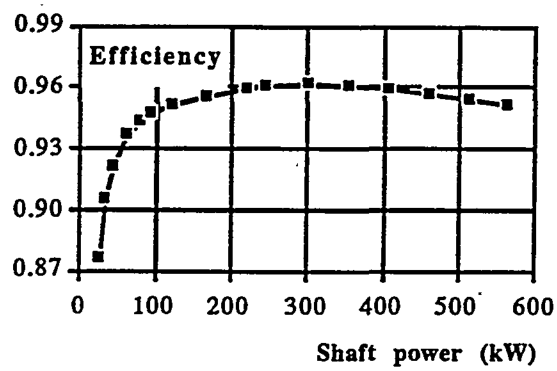

Fig. 6. Efficiency of the variable speed pm-generator as a function of shaft power.

A 500 kW low-speed asynchronous generator was designed. The number of poles was kept the same as in the permanent magnet machine designed and the frequency of the generator was 26.7 Hz. Asynchronous generators may not be built with fractional slot winding if the number of slots per pole and phase is lower than two. The air-gap leakage flux in this case would be unacceptably high. The machine was chosen to be two slots per pole and phase. The number of slots was 480 in the stator and 560 in the rotor. The maximum air-gap flux density was 0.8 T and the maximum flux density in the stator tooth 1.7 T. The stator and rotor core segments were made of 0.5 mm laminations. The stator and rotor yoke were made thicker than what was magnetically necessary in order to have a rigid structure. The height of the yokes was equal to that in the permanent magnet machine designed so that it was possible to compare the weight of the machines. The air-gap diameter was 3.2 m, the core length 0.6 m and the air-gap length 3.0 mm. The current density of the stator winding was 3.2 A/mm^2 and it was the same as in the permanent magnet machine designed. The cross-sectional geometry of the generator is shown in Fig. 7 and the main parameters are given in Table II.

The electromagnetic optimisation of the machine was done by the finite element method. The losses of the machine was calculated with a sinusoidal supply. The efficiency of the generator was 91.3 % and the power factor 0.54 at rated load. The maximum air-gap torque was 2.4 times the rated air-gap torque. The efficiency and the power factor of the generator are shown in Fig 8.

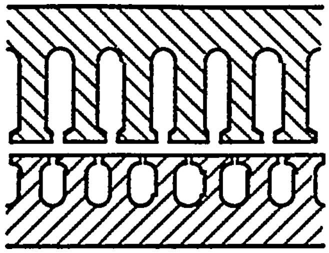

Fig. 7. Cross-sectional geometry of the ac-generator.

TABLE II
MAIN PARAMETERS OF THE AC- GENERATOR

	AC (40)
Number of poles	80
Number of phases	3
Number of stator slots	480
Number of rotor slots	560
Stator outer diameter [m]	3.4
Stator inner diameter [m]	3.2
Rotor inner diameter [m]	3.1
Air-gap length [mm]	3.0
Core length [m]	0.6
Connection	star
Rated voltage [V]	550
Rated frequency [Hz]	26.7
Rated current [A]	995
Rated output power [kW]	500

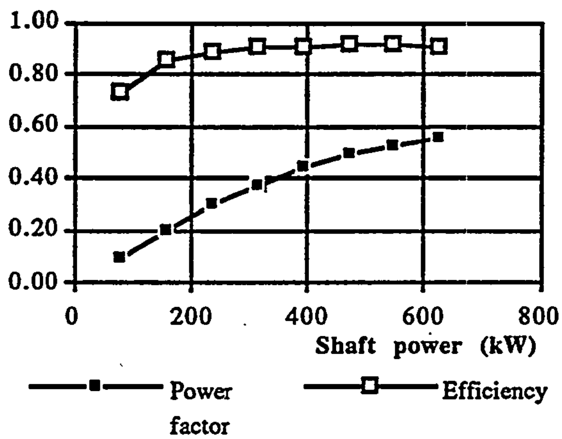

Fig. 8. Efficiency and power factor of the ac-generator.

III. COMPARISON OF THE GENERATORS

A directly driven low-speed permanent-magnet synchronous generator, a directly driven low-speed asynchronous generator and an asynchronous generator with a gear were compared. The rated power was 500 kW and the rated rotational speed of the turbine was 40 rpm. The characteristics of the machines were different and all the machines had their advantages and disadvantages.

In conventional wind power plants the generator is coupled to the turbine via a gear so that the generator can rotate at a speed of 1000 or 1500 rpm. A standard asynchronous generator can be used in this type of wind power plants. The advantages of a standard asynchronous generator include low weight, low maintenance costs, simple structure and a long life-cycle. The generator can be connected directly to the grid which results in a simple electrical system. However, the gearbox brings weight, generates noise, demands regular maintenance and increases losses. Furthermore, there can also be problems with materials, lubrication and bearing seals in cold climates. The total price of the 500 kW, 1500 rpm asynchronous generator is 170 000 ECU (including all taxes) and the price of the 500 kW gearbox is almost equal. The efficiency of an 1500 rpm asynchronous generator and a gearbox is 96 % and 97 %, respectively. The total efficiency is 93 % at rated load. The efficiencies of the low-speed permanent magnet and asynchronous generator and the 1500 rpm asynchronous generator with a gear are shown in Fig. 9.

In a directly driven, low-speed wind generator no gears are needed and many disadvantages can be avoided. The diameter of a low-speed generator is, however, rather large. There may be a great number of poles in a low-speed machine and the pole pitch and slot pitch may not become too small. For mechanical reasons a generator with a large air-gap diameter must have a rather large air gap. A frequency converter is usually needed in the low-speed machines. The converter makes it possible to use the machines in variable speed operation.

A low-speed asynchronous generator is one alternative to construct a directly driven wind generator. The air-gap diameter will be rather large. Because the large air gap the magnetising current will be extremely high. The power factor is 0.5 – 0.6 and the efficiency is about 91 % at rated load but they are small at part load. The asynchronous generator must be used with a force commutated rectifier in variable speed operation, because the stator needs a reactive magnetising current. The force commutated rectifier is more expensive than the diode rectifier and the efficiency is also smaller, for example 97.5 % of the IGBT-rectifier [11].

A low-speed permanent-magnet synchronous generator is a good alternative to construct a directly driven wind generator. Permanent magnet excitation allows the use of a smaller pole pitch than in conventional synchronous generators. The efficiency is good, for example 95.4 % in the generator designed. Synchronous generator can be directly connected to the simple diode rectifier. The efficiency is 99.5 % in normal operation [11]. High-energy magnets such as NdFeB permanent magnets must be used in the surface-magnet machine so that it is possible to provide an acceptable flux density in the air gap. The high-energy magnets are very expensive and the magnet material should be used effectively. It is, however, possible to demagnetise the magnet and therefore the machine must be designed carefully.

The weights of the active material of the low-speed permanent-magnet synchronous generator, low-speed asynchronous generator and asynchronous generator are shown in Table III. The rated power was 500 kW and the rotational speed was 40 rpm in the low-speed machines and 1500 rpm in the normal-speed machine. The active weight of the permanent-magnet machine was two times bigger and the active weight of the low-speed asynchronous machine was four times bigger than the active weight of 1500 rpm asynchronous generator. The costs of active material were almost equal in the low-speed permanent-magnet machine and in the low-speed asynchronous machine and four times higher than in the 1500 rpm asynchronous machine. The costs of active material are shown in Fig. 10. The material prices used in the calculations were: iron 3 ECU/kg, copper 6 ECU/kg and NdFeB magnets 100 ECU/kg.

The weight of a supporting structure and also the weight of a gearbox must be taken into account when comparing the different machines with each other. The weight of the supporting structure was 70 % of the weight of the active material in the 1500 rpm asynchronous generator and it was estimated that the percentage was equal in low-speed machines. The weight of the 500 kW gearbox and 1500 rpm asynchronous generator are 6500 kg and 2800 kg, respectively. The permanent magnet machine was 40 % lighter and the asynchronous machine was 20 % heavier than the 1500 rpm asynchronous machine with a gear. The weight of the generators and the gearbox are shown in Fig 11.

The material costs used of the supporting structure were 5 ECU/kg. The gearbox had three stages and the material costs were 26 000 ECU including electrical oil pumps. The material costs of the machines are shown in Fig. 12. The material costs were almost equal in the permanent-magnet machine and in the asynchronous machine with a gear but the low-speed asynchronous machine was 30 % more expensive.

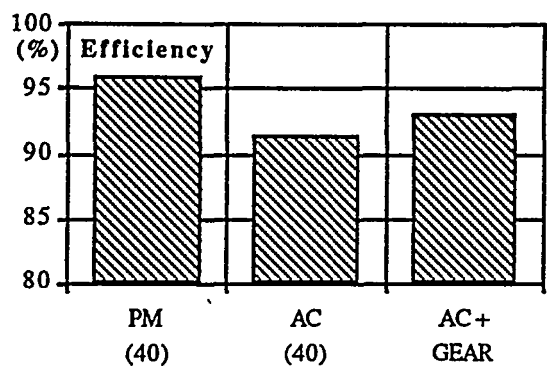

Fig. 9. Efficiency of the low-speed permanent-magnet (PM 40) and asynchronous (AC 40) generator and the 1500 rpm asynchronous generator with a gear.

TABLE III
WEIGHT OF ACTIVE MATERIAL

Material	PM (40)	AC (40)	AC (1500)
Stator core (laminated)	1870	2750	820
Rotor core (laminated)	-	1890	450
Rotor yoke (massive)	610	-	-
Stator winding (copper)	670	1080	250
Rotor bars (copper)	-	830	130
Magnets (NdFeB, 1.25 T)	140	-	-
Total active weight (kg)	3290	6550	1650

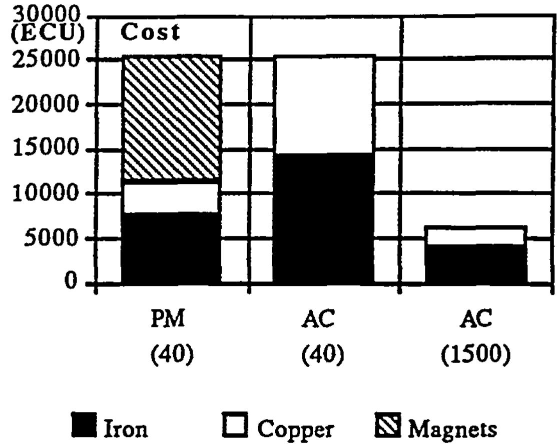

Fig. 10. Costs of active material.

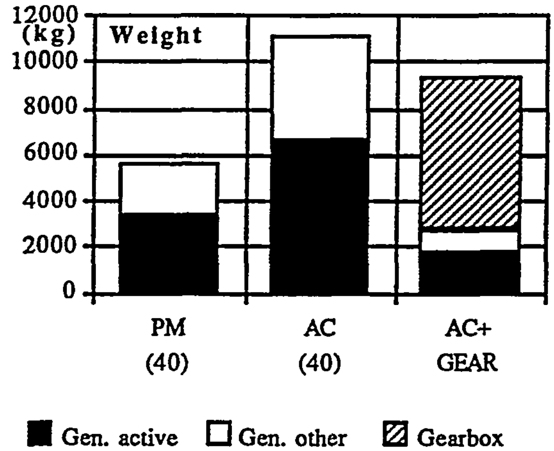

Fig. 11. Weight of the wind generators.

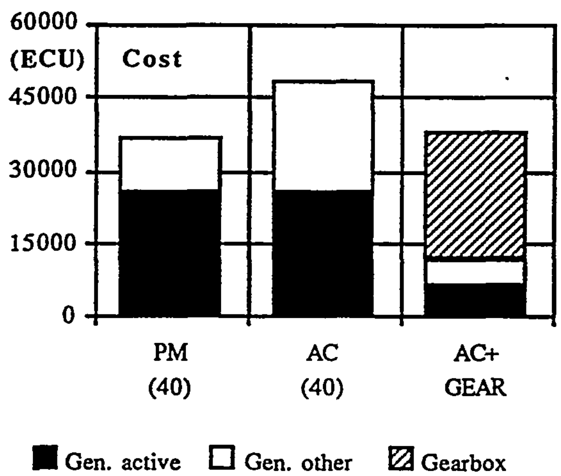

Fig. 12. Material cost of the wind generators and gearbox.

The constructions of the machines were very different. The diameters of the directly driven generators were rather large. The size of the 1500 rpm asynchronous generator was small but a gear must be used. The dimensions of a typical 500 kW gearbox are 1.4 x 1.7 x 1.7 m. The size of the machines is shown in Fig. 13. The size of the permanent-magnet generator was 40 % smaller than the size of the asynchronous generator with a gear.

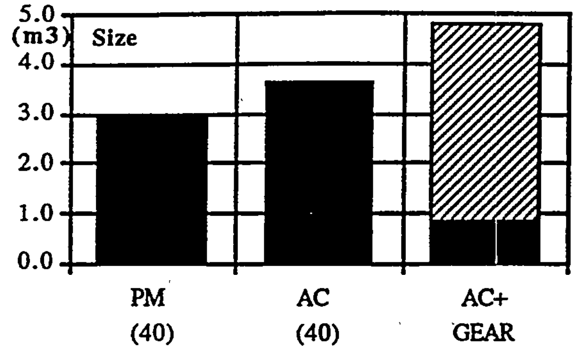

Fig. 13. Size of the machines.

IV. CONCLUSION

The electromechanical system of a wind power plant usually consists of three main parts: turbine, gearbox and generator. The rotor of a wind turbine rotates typically at a speed of 20 – 100 rpm. The generator is coupled to the turbine via a gear so that it can rotate at a speed of 1000 or 1500 rpm. However, the wind power plant can be simplified by taking off the gear and by using a directly driven low-speed generator.

A 500 kW, 40 rpm directly driven permanent-magnet synchronous generator was designed for this study. NdFeB magnets were mounted on the surface of the rotor yoke. The air-gap diameter of the machine was 2.5 m, the length 0.5 m and the active weight 3290 kg. The efficiency at rated load was 95.4 %.

The permanent-magnet generator was compared with a directly driven asynchronous generator and an asynchronous generator with a gear. The diameter of the asynchronous generator designed was 3.2 m, the length 0.6 m and the active weight 6550 kg. The efficiency at rated load was 91.3 %. The total weight of a typical 500 kW wind generator and a gear was 9300 kg. The efficiency at rated load was 93 %.

The total weight of the permanent-magnet generator designed was two times bigger than the weight of the typical 1500 rpm asynchronous generator, but 40 % smaller than the weight of the asynchronous generator with a gear. The weight of the low-speed asynchronous generator was 20 % bigger than the weight of the asynchronous generator with a gear. The efficiency of the permanent-magnet generator was also much better than the efficiency of the asynchronous generator with a gear and the low-speed asynchronous generator. The material cost of the permanent-magnet generator and the asynchronous generator with a gear were almost equal. The size of the permanent-magnet generator was 40 % smaller than the size of the asynchronous generator with a gear.

A low-speed permanent magnet synchronous generator would be a good alternative to construct a directly driven wind generator.

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Reducing Costs of Wind Power with a Gearless Permanent-Magnet Generator

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ABSTRACT: This paper examines a disc-type axial-field permanent magnet generator (PMG) utilizing the latest generation of permanent magnet material, namely $Nd_{15}B_8Fe_{77}$. A frequency converter (FC) is needed to keep the system synchronized with the grid. It also offers a possibility to use variable speed. The main advantages of this novel system compared to the conventional one are a higher overall efficiency, better reliability, reduced weight and diminished need for maintenance, all contributing to the cost-reduction of wind power.

1 INTRODUCTION

The rotational speed of a 100-500 kW wind turbine is about 18-60 rpm, while asynchronous generators (ASG) used in the wind power plants need 800-1500 rpm. That is why an expensive and heavy gearbox is needed between the turbine and the generator. In order to achieve a gearless construction of a wind power plant a novel generator with a large number of poles (about 100-150) is required.

A such generator is being developed at Tampere University of Technology. Permanent magnets and axial field allow a large number of poles without a reduction in efficiency as compared to traditional synchronous machines of the same rating. The permanent magnet generator (PMG) is technically comparable to a syncronous machine with constant excitation. Therefore a frequency converter is required to allow the rotational speed to vary according to wind gusts. The frequency converter (FC) stabilizes the power output from gusty winds.

A comparison is made between the traditional drive train technology, i.e. a gearbox, an asynchronous generator, compensating capacitors and a soft starter and novel one including a gearless permanent magnet generator (6-phase), a frequency converter and a line filter (Fig. 1).

2 OPTIMIZATION OF PMG

Price of the PMG depends strongly on the amount of permanent magnet material used: The more magnet material is used. the stronger is the magnetic field in air gap and less copper is needed.

Other decisive factor is radius of generator: The longer the radius, the less magnet material and copper is needed, but weight and cost of supporting structure increases with square of the radius and a large generator itself should be strong enough to resist wind forces.

In the cost calculation the losses over the lifetime are also included in a graph (Fig.1.) of total costs of active material (magnets, copper and iron) over twenty years lifetime, when 5% real interest rate is used on capital costs and 30 p/kWh for loss energy.

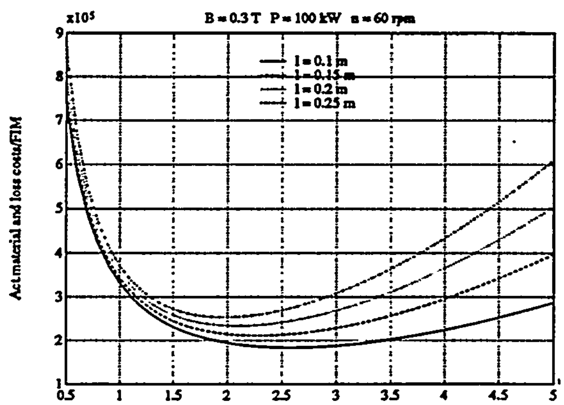

Fig. 1. Active material and losses of PMG as a function of radius on different air gap widths

Cost of active material and losses are clearly minimized, when radius is approx. 2.5 m, but if supporting structure, assembly and total weight are taken to account, radius can be kept on acceptable level of 1 m.

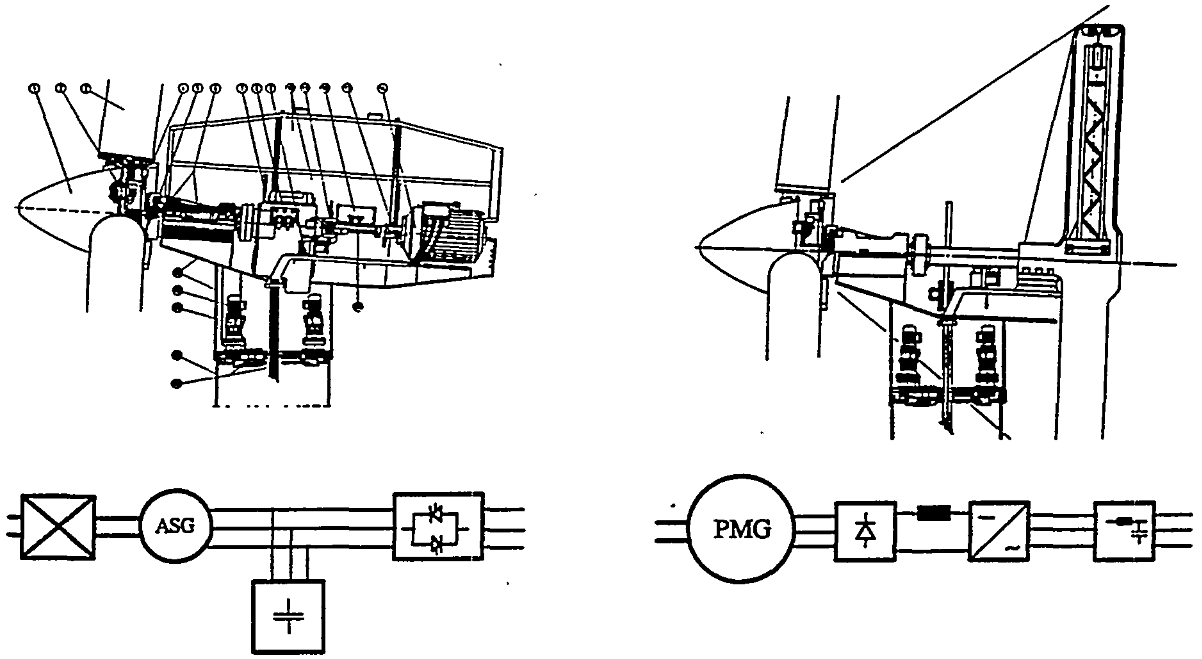

Fig. 2. Compared drive train options, with circuit diagrams. a) traditional drive (Nordtank 150) b) PMG-drive

3 COMPARISONS OF WEIGHT AND COST

3.1 WEIGHT OF THE DRIVES

In design of wind turbines reduction of towerhead weight is favourable, because the tower can be made lighter. In weight comparison we concentrate on gearbox and ASG vs. PMG, because FC is usually placed in the root of the tower for better access and serviceability.

In PMG the weight of supporting structure is evaluated to be about the same or a little less than active material (magnets, copper and iron core) in preliminary calculations.

With these assumptions it can clearly be seen that PMG drive weighs only half of traditional drive. This is due to heavy gearbox, of which weight increases linearly with power, while in ASGs weight/power-ratio is constantly falling as power increases.

TABLE I
WEIGHT COMPARISON BETWEEN GEARBOX&ASG VS. PMG (IN KG) [1]

power/kW	gearbox	ASG	Total	[a]PMG
50	800	360	**1 160**	**400**
100	1 000	700	**1 700**	**800**
225	2 000	1 100	**3 100**	**1600**
500	5 300	2 100	**7 400**	**3 400**
1 000	10 000	3 600	**13 600**	**8 000**

[a] Radius of PMG: 50 kW: r=0,7 m, 100 kW: r=1 m, 225 kW: r=1,4 m, 500 kW: r=2 m, 1 000 kW: r=2,5 m

3.2 PRICE OF THE COMPONENTS

PMG requires FC for variable speed to maximize energy capture and to syncronize the PMG with the grid. FC is based on current-source inverter technology [2] for simplicity and minimization of the amount of active compoments, i.e. power transistors/thyristors.

TABLE II
COST OF GEARBOX, ASG, COMPENSATING CAPASITORS AND SOFT STARTER (IN FIM)

power/kW	gearbox	ASG	[a]kond&SS	total
50	40 000	22 000	17 100	**39 100**
100	65 000	30 000	23 676	**118 676**
225	100 000	50 000	38 335	**188 335**
500	275 000	100 000	84 821	**459 821**
1 000	500 000	150 000	[b]162 500	**812 500**

[a] in designing of capasitors 0.7 times of kVar per kW is used e.g. 100 kW turbine requires max. 70 kVar compensating reactive power.

[b] price of 1000 kW soft starter estimated at 100000 FIM

Manufacturing costs of the PMG are approximately 40% of total material price, excluding magnets. In FC this manufacturing supplement is evaluated to be about 100% of the price of materials in small-series production.

TABLE III
PRICE OF PMG AND FC (CALCULATED; IN FIM) [3]

power/kW	total price of PMG drive	rel. price to ASG drive/ %
50	77 000	190
100	150 000	127
225	220 000'	117
500	490 000	106
1 000	900 000	110

4 EFFICIENCY

Only drive trains are compared versus one another, blades and other compoments used are the same. Calculation of the efficiency of various wind turbines is based on typical power coefficient (c_p)-curve of three-bladed rotor (Fig. 3.).

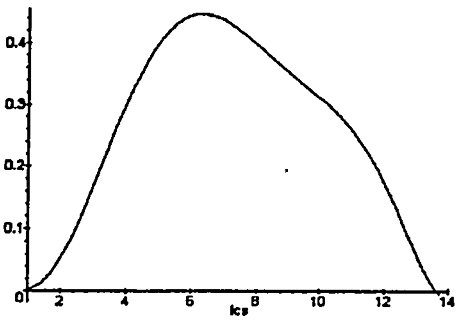

Fig. 3 c_p-curve of three-bladed rotor (lcs=tip speed ratio=tip speed to wind speed-ratio)

For results to be independent of size of the turbine, all units are scaled to per unit values, using as a base value nominal power of wind turbine and wind speed, at which it reaches this power.

The method used is the same as described by Grauers [4], with following exceptions:

1. Variable speed range of the wind turbine is restricted to the area of 50..100% of nominal rotational speed, not above 29%, to avoid resonance in tower structures.

2. Stall-regulated rotor is used, which reduces energy capture in constant-speed drives.

3. Units are scaled according to the point where the whole power plant reaches its nominal power, not the turbine.

Power curves of various wind power plants are drawn (Fig. 4). In the curves can be seen, how close 2-speed constant and variable speed drive are each other in region v=0.5...0.8 where most of energy production takes place. Initial assumpitons on losses are more closely described in the appendix.

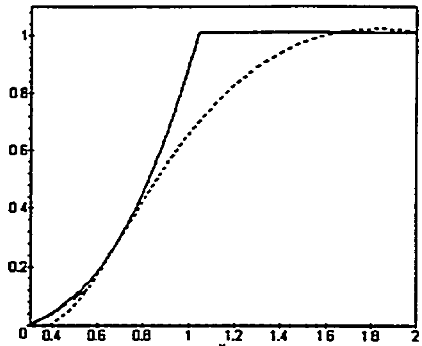

Fig. 4. Power curves of various turbines: Variable-speed (line), constant speed (broken line), with lower speed (dotted line)

Using weighting function, w, which here is Weibull distribution of wind speeds energy production in different median wind speeds is calculated by (1), where v is wind speed, c form factor (here c=2) and v_m median wind speed, all in per unit values.

$$w(v,c,v_m) = v_m^{-c} Log(2)\, c\, v^{(c-1)}\, e^{(-Log(2)(\frac{v}{v_m})^c)} \qquad (1)$$

Is formula results following curves with different v_m values in Fig. 5:

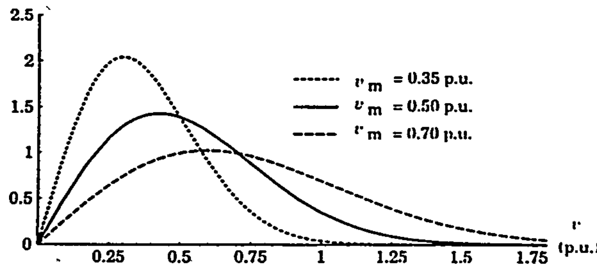

Fig. 5. Weibull distribution for three different median wind speeds

Multiplying power curve with weighting function and integrating over cut-on to cut-off wind speeds total energy production is obtained with (2).

$$e(v_m) = \int w(v, v_m)\, p(v)\, dv \qquad (2)$$

As a result the following graphs of energy prodcution of constant-speed drives related to PMG drive (Fig. 6) are obtained on various wind speed sites. Base wind speed, that where plant reaches it's nomial power, e.g. v_N =12 m/s, v_{MED}= 6 m/s is v_m = 0.5.

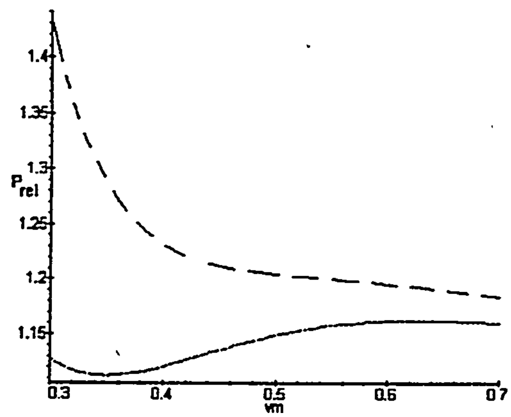

Fig. 6. Relative energy capture of variable speed drive compared to 2-speed constant drive (line) and 1-speed drive (broken line)

In comparison to 2-speed constant drive, which nowadays has dominating position in wind power plants, produces variable speed-fixed pitch configuration 10-15% more energy annually, mainly due to closer tracking of $c_{P,Max}$ -point, where turbine draws energy from the wind with the greatest efficiency.

5 OTHER FACTORS

There are other points in favour of gearless construction, which are not easily converted onto monetary benefits. In the traditional drive the gearbox must usually be over-dimensioned with factor 1,5-2, ASGs over 500 kW must be equipped with fluid coupling to dampen the effects of gusts. An alternative, large slip would cause too many problems with heating in the ASGs.

In pitch-regulated plants slower pitching suffices and in stall-regulated, the beginning of stall is achieved more precisely due to variable speed.

On erection of wind power plant lower weight constraints for crane, lighter parts make it possible to design a crane which utilizes the tower of the plant as a carrying structure.

5.1 ENVIRONMENTAL FACTORS

Variable speed offers better aestetical appearance at low wind speeds, due to more peaceful running of the turbine than with constant speed drives. Variable speed turbines are also less noisy due to lower blade tip speed in low wind speeds, therefore they can be situated closer to residential areas.

They offer elimination of gearbox noises, less power fluctuations due to wind gusts. Energy of the gusts is stored temporarily in the rotating mass of the turbine. With gearbox the need of oil changes and risk of leaks is eliminated. Cons are harmonics fed to the grid, which require proper filtering.

5.2 STRESS ON BLADES

For variable speed there is diminished need of material and cost because shaft torque is reduced by 50%, although stress on wind direction is not diminished [5]. During wind gusts turbine acts again as a flywheel storing extra energy temporarily unlike in constant-speed drive, where moment stroke goes through the system causing stress in gearbox and fluctuations on grid voltage.

5.3 MW-CLASS MACHINES

In reducing costs of future MW-class machines the role of this new design as PM-generator is crucial. Advantages of PMG-FC are pronounced when reduction of losses over 20 year are taken into account. Further cost reductions are expected as price of the new permanent magnet materials and power electronics falls. Abilities of components of power electronics to handle higher voltages and currents are also improved and losses reduced. Cost reductions can be achived by utilizing transformer inductances for filtering the harmonics of the FC.

6 CONCLUSIONS

An electrical drive consisting of 20% of the total price of a wind power plant, may cost 5% more, if it produces 1% more energy, because additional energy capture is in favour of the whole plant. As variable speed achieves 10-15% more energy capture, it can therefore cost 50-75% more to keep the price of electricity same. PMG drive costing only 6-27% more in size classes 100- 1 000 kW reduces the price of electricity produced with 5-10%, compared to ASG drives. In this figure is not considered the cost-reductive effects of other factors mentioned in chapter five, which may also lower the price of electricity with 5-10%.

Savings on weigth are clearly due to heavy gearbox, ASG itself weights less than gearless PMG, thanks to more compact construction.

Preliminary calculations are deliberately based on cost and weight, although material and manufacturing costs are stongly dependent on the cumulative amount produced, where odds are for the standard technology. In the future, however, the prices of power electronics and permanent-magnet materials are excepted to come down, as the prices of gearboxes and ASGs remain nearly the same for the maturity of this technology. For this reason, invesment cost difference will become smaller.

Absolutely reliable results can be obtained at a point when the first series of the drives has been actually built and tested, however up-scaled modelling looks promising. Further comparisions should be based also on physical quantities, such as the area of silicon in power electronics, copper and iron required, resulting in more independenence on amount of units produced.

Results show savings on weight and cost compared to the traditional design. Furthermore it can be said that this new generator may be considered for wind power plants as well as other low-speed power generation applications, e.g. micro-hydropower.

APPENDIX

Losses of the gearbox on constant-speed drives is calculated by (3), where t_t is torque of the turbine (all values in per units)

$$t_{lossgear}(t_t) = 0.5\% + 2.5\%\, t_t \quad (3)$$

Losses of the asyncronous generators (4) depend on the output power of the generator, p_g.

$$p_{lossASG1} = 0.026 + 0.011(p_g + 2p_g^2) \quad (4)$$

For the lower speed of two-speed generator losses can be modelled with (5).

$$p_{lossASG2} = 0.013 + 0.033(p_g + p_g^2) \quad (5)$$

Losses of PMG generator are modelled with

$$p_{lossPMG} = 0.025 + 0.025 p_g + 0.01 p_g^2 \quad (6)$$

Losses of FC and line filter, where p_{con} is power of the converter.

$$p_{lossFC} = 0.012 + 0.031 p_{con} + 0.0096 p_{con}^2 \quad (7)$$

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ABSTRACT

The reason for the investigation was to clarify possibilities to produce windenergy on the small islands. The aim was to clarify the costs and energy earnings of the powerplants erected on the coastline, too. Furthermore the target was to measure the windspeeds on the offshore island and calculate the building costs. Finally the purpose was to calculate the price of energy produced on a small offshore island.

The Pori windmill was connected to the net 4.9.1993. The production of the powerplant has been without bigger problems. The few problems have not affected to the production.

This windmill was assembled and tested in a Finnish workshop. That gaves valuable experience for the windpowerplant production. The erection of 10 similar power plants elsewhere in Finland the same year in 1993 gives a good base to compare location and erection costs of the windpower plants. The price and erection costs of those 10 powerplants are some over 7000 FIM/kW. Pori plant, which was assembled as an unique machine in Finland, was more expensive.

Based on our research and wind statistics the island outside Pori town is the best place for a new windpowerpark of the Finnish coastal offshore areas. It can produce 750 MWh in a year with the 300 kW turbine.

The erection cost on offshore island deviates not so much as the similar powerplant onshore. For example the expensive road are not needed.

If the windmill will be located onshore, the turbine should be placed so that there is no obstacles from any main wind directions. On the coastline the wind conditions are nearly on the offshore level, if the main directions on Pori area: north and south - south west, are without obstacles. The other wind directions have small effect to the power production.

The energy price of the windpower plant located on the small offshore island is 13,7 p/kWh based on 52,5% own financing and 26,0 p/kWh with 100% own financing with 5% real interest, 20 years payback and one percent service cost. The calculation is based on three 300 kW windmill, investment cost is 7200 FIM/kW and those are producing 750 MWh/y each.

The average power production is highest during the winter, when the high tariff is valid, too. On daytime the power consumption and the peak wind energy production do not follow each other very much. However, the production peaks are on the afternoon.