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TECHNICAL PAPER

WIND ENERGY DEVELOPMENT THE DANISH EXPERIENCE

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WIND ENERG' DEVELOPMENT, THE DANISH EXPERIENCE

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Abstract

Wind energy is expected to play a significant role in the future energy supply. It is a non-polluting and sustainable energy source, which on a technical basis has proved to be an economically feasible and thus a realistic alternative to traditional power production. This conclusion may be drawn from Danish experiences where energy planning comprises a significant contribution from wind energy.

Since 1976 approximately 3000 wind turbine units have been installed and connected to the grid in Denmark, representing a capacity of roughly 340 MW out of a grid capacity of 8,000 MW. These units are all grid-connected and the unit sizes range from 30 kW to 450 kW. The installed wind energy capacity represents a substantial development of technologies for wind energy utilization during the last 15 years, involving participation from many sides: research institutes, electric utilities, the national energy administration, and private industry.

The development has resulted in a considerable improvement of the technical and economic performance of wind turbines along with increased reliability and durability. The successful development has been strongly supported by comprehensive government programmes, i.e. establishment of a national wind energy research and development programme, establishment of the Riso Test Station for Wind Turbines and a subsidy scheme for private turbine owners. The improved economic performance is partly the result of a development in rotor size of commercially available wind turbines. In 1981 the largest commercial wind turbine size in Denmark was 55 kW, while today it is close to 500 kW. In the same period the average energy production per installed unit capacity almost doubled, due to enhanced aerodynamic rotor design, increased tower height and improved overall design and production methods.

In parallel to this commercial development, the Danish utilities have developed and constructed a number of megawatt-size wind turbines on a pilot project basis.

In general terms the wind energy resources in Denmark are rather good, and many suitable sites exist. However, the development is affected by a relatively high population density, which implies many restrictions on land use. Consequently, investigations are presently made to evaluate the possibilities of off-shore located wind turbines. Wind energy developments similar to the Danish are taking place in other industrialized countries, the perspective being an increased use of wind energy all over the world, also in developing countries. At present approximately a 2000-MW wind turbine capacity is installed on a worldwide basis, representing an investment of 2-3 billion US$.

In local communities with no connection to a national grid special attention should be paid to hybrid systems such as wind-diesel and hydro-wind systems. Because of the high price of diesel oil, wind power may be found competitive in many cases as a supplement to diesel generated electricity in such isolated grids. In order to facilitate a significant development in application of hybrid systems in developing countries, further demonstration and development in addition to a substantial technology transfer is required.

1. INTRODUCTION

A global "energy optimism" prevailed in the sixties. An abundance of relatively cheap oil was available on the world market, and at the same time there was a strong belief in the prospects of nuclear power as a major element in the future energy supply system. The seventies revealed a vulnerability of many nations related to energy supply strategies based too strongly upon oil, causing utilities around the world to use a larger fraction of coal in the thermal power plants. Furthermore, there was a growing concern of environmental aspects of energy conversion and use: for fossil fuels focus was on SO_2 NO_x and particles, and for nuclear power plants risks connected to operation, to storage of waste material, and to the potential relations between civil and military applications of nuclear technologies. During recent years carbon dioxide from burning fossil fuels has been on trial suspected of contributing to the so-called greenhouse effect. In the eighties the world market oil prices have gone down, but the problems of how mankind can create a sustainable economic and social development on a global scale seem as prominent as ever.

On this background an accelerated development of renewable energy technologies has taken place all over the world, among which are wind energy. This paper summarizes this development based mainly upon experiences from Denmark and other industrialized countries. However, before entering into a description of the wind energy technology, the modern wind turbine concept is briefly outlined to the benefit of the non-expert reader.

1.1 Wind Turbine basics

Most people will associate the term windmill with an apparatus pumping drinking and irrigation water, driving grain mills and the like. A direct transfer of wind energy into mechanical energy has been known for thousands of years, and in many places of the world the ancient technology of wind energy still fulfills a mission in society. After the introduction of methods of energy production by means of fossil fuels, the windmill has gradually lost its importance in competition with the compact electricity generator and later on the electric distribution grid.

Over the years, in the age of electricity, several attempts have been made to utilize wind energy for electricity production, though with little commercial success. It was not until the oil crisis in the mid seventies where energy prices increased to unprecedented heights that a serious interest in wind energy was triggered.

A modern windmill - or wind turbine as is the preferred word nowadays - produces electricity. It is equipped with a two or three-bladed rotor to capture the wind. The rotor blades are slender, with cross sections similar to those of airplanes. The length of the blades is 10 to 50 m, and the rotational speed of the blade tip is of the order 150 to 300 km/hour while in operation, depending on the machine size. The rotor extracts a certain fraction of the energy in the air flowing through the it swept area of the rotor. Typically, this fraction is 30-35%. The aerodynamic torque is transferred to the electric generator through a gearbox. The generator may be an AC or DC-generator, the size of which - unlike other power producing aggregates - is a secondary choice: the size is basically chosen to fit the aerodynamic properties of the rotor. Thus, the key figure for a wind turbine is the "wind capturing area" - the swept area of the rotor, or simply the rotor diameter.

Power plants are traditionally characterized by the installed capacity of the electric generator. As indicated, this makes sense only in part when describing wind power units.

When wind turbines are connected to a major grid, the control may be relatively simple. Using an induction generator as is the most common, the revolution speed of the turbine, and thereby the frequency of the machine's generator, is kept constant by the much larger conventional generators connected to the grid. The principal function of grid-connected wind turbines is to lower fuel consumption of the conventional units. As a first approximation the economy of the grid-connected concept can be assessed by comparing the amount of fuel saved with the amortization of the investment in the wind power plant. The grid-connected wind turbine may now be considered proven technology, and the development efforts have shifted from making the machines work to bringing down the production costs and improving the efficiency.

The wind/diesel system, on the other hand, has attracted little attention from industry until recently and may therefore be expected to take a few more years to reach technological maturity. A wind/diesel system is a hybrid system, the basic components of which are a wind turbine and a conventional diesel generator, the two units having approximately the same power capacity. While the wind turbine may very well be identical to the grid-connected machine, significant problems arise in the design of the control system for the integrated system. The probable use of wind/diesel systems will typically be in remote areas and isolated communities.

A sub-category of the wind/diesel concept is the battery charging wind turbine. The (DC) generator in such a machine is typically a few hundred W and the rotor up to a few meters in diameter. Although the worldwide "installed" capacity of these machines is very small compared to the grid-connected concept, the battery-charging machines are produced in large numbers, most notably in the People's Republic of China, serving nomads in remote areas.

2. WIND ENERGY DEVELOPMENT IN DENMARK

2.1 Historical Background

Although the wind has been utilized for centuries in Denmark, the Gedser wind turbine which was operated in the years between 1957 and 1967, is considered the start of the modern era of wind energy in Denmark. The machine had a 24m diameter rotor and was rated at 200 kW, built for the purpose of evaluating the technical and economic prospects of utilizing wind energy for electric power production.

Shortly after the first oil crisis in 1973/74 a report on the prospects of wind energy was prepared, partly based on experiences from the Gedser machine. It concluded that

- conversion of wind energy into electric energy was a favorable technical option, and that

- up to 10% of Denmark's electricity consumption could be covered by wind energy without any need of energy storage and without causing any serious control problems in the general power system, and that

- a development of cost effectiveness of the wind turbines was needed.

The report was the first step in a process of long term research and development programmes in wind energy issues - based on public as well as private funding - and the establishment of a test centre for wind turbines in 1978 at Risø National Laboratory.

2.2 Public Support Programmes for Wind Energy

The technological development and practical implementation of wind energy plants have found general support in Denmark. In this section we will give a brief survey of various public supporting schemes.

Wind Energy Research Programme. Under the auspices of the general energy research programme of the Ministry of Energy a programme on wind energy was carried out. The programme consisted of a small-scale programme aimed at technology development for industrially manufactured wind turbines (30-50 kW in the beginning), and a large-scale programme aimed at MW-sized wind turbines. In the period between 1976 and 1987 subsidies for wind energy research sum up to about DKK 120 million, which amounts to 10% of the entire energy research programme of the Ministry of Energy. Since then - with maturing of the technology and strengthening of the industry - national research funds have been reduced and the direct subsidies for private wind turbine installations have been gradually reduced and were finally removed completely in 1989.

In the field of small-scale turbines general studies of wind turbine aerodynamics, structural viability, safety and power regulations have been brought into focus. The development of large-scale wind energy conversion systems, on the other hand, has taken place on the basis of a cooperation between the government and the electric utilities. In this work emphasis has been placed on technology development, wind resources, identification of suitable wind turbine sites, and compatibility with the grid.

Agreements on Charges for Supply to the Grid. The private owned wind turbines are connected to the grid which effectively functions as storage because in most cases the owner cannot consume the production in high-wind periods while needing another energy source in sold periods. Therefore, the owner sells electricity to the power company. The agreement between the electric utilities and Danish wind turbine plant owners includes two rates for electricity supplied to the grid from privately-owned wind power plants.

a. Surplus production from wind turbines connected to the owner's private electric installation is purchased by the utility at a price equivalent to 70% of the utilities' net selling price (i.e. exclusive of State energy tax and VAT) to household consumers.

b. Electricity produced by wind turbines with a separate installation - which conform to the conditions required to obtain a subsidy - is purchased by the utility company at a price equivalent to 85% of the net selling price to household consumers.

Also, the wind turbine owner is exempted from State energy tax and VAT for the "avoided purchase" from the power company.

Large Scale Wind Turbine Projects. The utilities finalized construction of a 2-MW wind energy plant in Southern Jutland in 1938 as the latest of a series of MW-size machines. The project is a scaled-up model of one of the first large-scale wind turbines made as a part of the R&D programme. The machine has a rotor diameter and hub height of 60 m. The costs of design, manufacturing and installation of the turbine was approx. 10 million US $. In the eastern part of the country, the utilities have established a wind farm on the island of Masnedø in Southern Zealand. This wind farm comprises 5 turbines each with 750-kW installed capacity and a 40-m rotor diameter. They were connected to the grid in 1986, the total costs being 9 million US$. The Masnedø turbines are instrumented for performance monitoring to collect data in order to utilize the experience gained.

The Masnedo wind turbines can be considered the second generation of one of the Nibe wind turbines, namely the pitch-controlled Nibe-B. The two Nibe wind turbines, a stall and a pitch controlled each of 630 kW, were installed in 1979-80 and are in spite of being prototype and research turbines still in operation (Nibe-A: 6146 hrs, Nibe B 23792 hrs, april 1991).

The Commission of the European Communities has supported several projects, the project support being conditioned by the conduct of certain monitoring programmes during the test period.

2.3 Wind Resources

A most important component in the complex of wind energy sciences forming the so-called wind energy technology is identifying the available wind resources. It is illustrated by the fact that the amount of energy in the wind roughly speaking is proportional to the wind speed cubed, i.e. if the annual average wind speed at one site is twice as high as at another site, then the available wind energy at the first site is $2^3 = 8$ times as high as at the second site!

Therefore, the Danish Ministry of Energy gave priority to the development of a "wind map" for Denmark, the idea being to facilitate a selection of suitable wind turbine sites. Risø National Laboratory performed the task and produced by 1980 Wind Atlas for Denmark, a publication, which was not a collection of maps of good wind sites, but a computational method, ref. [1], [2], and [3].

The backbone of the method is the assumption that the geostrophic wind speed distribution (the wind speed at high altitude, i.e. 3-5 km above ground level) is the same for the 500 x 500 km square in which most of Denmark can be contained. Analysis of available data basically confirmed this assumption, leaving one problem to be solved, i.e. relating the geostrophic wind speed to the ground wind speed. As some readers may know, the Danish landscape is rather flat, with maximum altitudes of 150 to 200 m above sea level. It was therefore found that only local characteristics of the terrain surface roughness would be of importance to the vertical variation of wind speed. Thus, for each site the terrain is divided into 12 sectors, and in each sector the terrain is categorized in 4 groups: water, open land with no vegetation, farmland with relatively little vegetation, and urban areas with many buildings and tall vegetation.

Through the employment of atmospheric boundary theory, the slowdown of the wind - relative to the geostrophic wind - at the height considered is calculated in each of the 12 sectors. And lastly the contributions from the sectors are added to produce the final product of the wind atlas analysis: the frequency distribution of wind speeds at the center of the intended wind turbine rotor. The Wind Atlas Method also suggests ways to make corrections for nearby obstacles such as buildings and tall trees, and possible speed-up effects when a wind turbine is placed on a hill. Figure 1 is a schematic representation of the wind atlas method.

The method has been used for siting of more than 1000 wind turbines over the last 8 years and has proven successful in predicting the power production from wind turbines.

2.4 The Risø Test Station for Wind Turbines

The curse of newly developed technology is always teething troubles, initial problems which may scare away potential users and thus prolong the time needed to ripen the technology. In the case of wind energy, a fair amount of problems has certainly been encountered, resulting in some reservation from decision makers as to the feasibility of the technology. Looking back, it seems evident that the establishment of wind turbine test centers has played an important role in overcoming the initial problems and supporting the development of the wind energy technology.

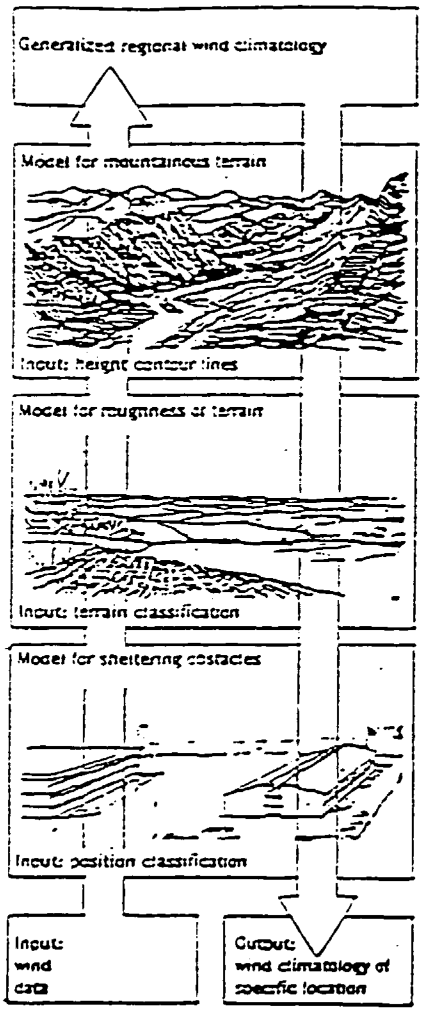

Figure 1. Schematic representation of the method used in the Wind Analysis and Application Programme. From a meteorological station a data set of measured wind speed and wind direction is supplied. Furthermore, an accurate description of the surroundings is given: orography, terrain type, i.e. water areas, open farmland, forests etc., and details of nearby sheltering obstacles such as buildings and windbreaks. The programme utilizes this information to calculate a generalized wind climate for the region. The specific wind climate at a specific location is then calculated by an inverse calculation employing the specification of the surroundings.

The Test Station for Wind Turbines was established in 1978, financed by the Danish Ministry of Energy and located at Risø National Laboratory. The initial role was to provide technical support to the then infant wind turbine industry. However, since 1981 The Test Station for has been authorized by the Ministry of Energy to review the turbines and issue the so-called System Approval Certifications. Until 1989, subsidies were given to the wind turbine owner for machines posessing such a certificate.

The system approval procedure contained the following activities:

- Check of safety systems and load-carrying capability of the machine.
- Engineering review of the design.
- Spot check control of the manufactured wind turbines, including inspection at the factory.
- Measurement of the power curve and safety system operation.
- Test of the wind turbine at the Test Station or in the field, including a number of more or less standard tests such as operational viability, power performance, power quality, and magnitudes of loads.
- Separate testing of the blades at the Test Station.

A general System Approval was issued on the basis of this integrated wind turbine analysis. For prototypes or in lack of complete documentation of the design, a certificate limited to one or a few machines were issued, thus providing the manufacturer with the opportunity to prove that the general performance of his product is acceptable.

Wind energy in Denmark being an established industry with mature products implies that more comprehensive requirements for the certification now can be honored. Based on a general consensus between manufactures, investors and the authorities efforts since the beginning of 1988 have been made to establish the new certification system. A new law giving the legal basis for the new certificate system passed the Parliament 1990, and the new certification system started in May 1991.

Systematic quality assurance is further emphasized throughout, and the system comprises a verification of both the design (type approval), the quality assurance system for the manufacturing, the installation, and requirements for the operation and maintenance.

The new system aims at ensuring the quality and performance of all Danish wind turbines, including those for export. Several institutes, including international classification societies and others with relevant expertise take part in the approval procedure and perform tasks in connection with approvals, tests, and certifying activities. The Test Station for Wind Turbines retains a central role also in the new system of approval.

The certification however, is only one element of the Test Stations activities. With the general objectives to contribute to the development of wind power technology, to evaluate and certify, performance, and new developments (concepts) of wind turbines, and to be a center of wind power technology expertise, the Test Station has four main categories of activities:

1. Basic and applied research in order to acquire new knowledge relevant to wind energy and wind turbine technology and develop the theoretical tools needed to advance the art.

2. Certification of wind turbines with the aim of ensuring the safety and quality and assisting in the dissemination of information to the industry including recent R&D results.

3. Testing of wind turbines and major components for both research and certification purposes.

4. International cooperation, standardization work and consultancy assistance to authorities, governments agencies, electrical utilities, and other planners and users of wind power.

The Test Station performs basic research in aerodynamics and structural design, fatigue and load modelling of wind turbines as well as general wind turbine technology. Also innovative research is undertaken, investigating possible new wind turbine concepts and new ways of wind energy utilization. The Test Station staff has built up a thorough knowledge of the Danish wind technology and provides industry with advisory assistance to an extent not conflicting with the independent status of the Test Station.

2.5 Achievements in Wind Energy Technology and Design

In terms of technical concepts, two parallel development processes have taken place. Direct government initiatives represent one of these lines of action, aiming at the development of MW-size wind turbines, i.e. rotor diameters of 40 to 100 m. Initially, some analyses seem to indicate that the lowest cost per kWh would be found for those very large machines. As of now, however, very little commercial activity has taken place in the wake of the national MW-projects, and it could be claimed that the most significant spin-offs are design tools and general wind turbine know-how.

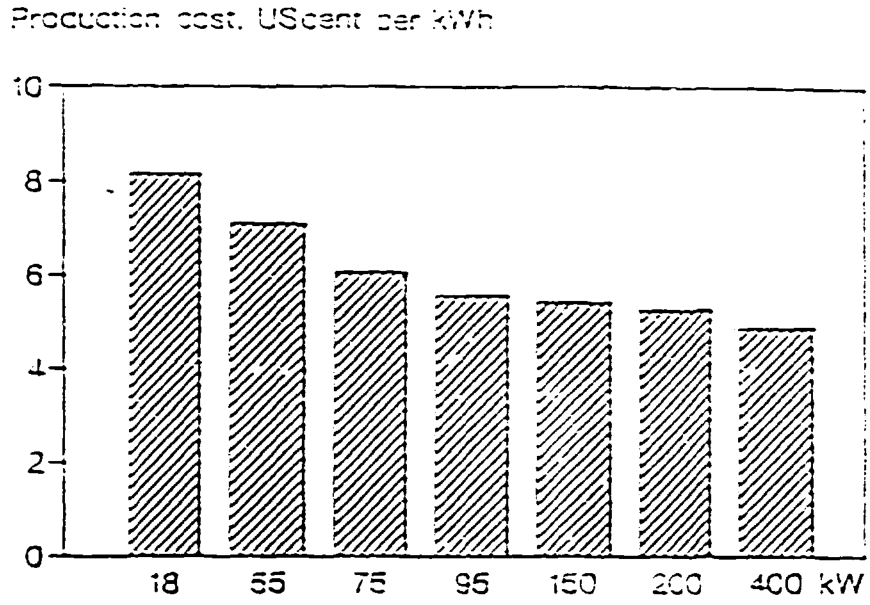

Figure 2. Production costs (US-cents/kWh) of land-based wind turbines as a function of installed capacity. A lifetime of 20 years is assumed.

The other line of development is represented by the vast majority of the total worldwide installed wind turbine capacity. These machines are commercially available with installed capacities ranging from 30 to 450 kW, corresponding to rotor diameters of 12 to 37 m. The size has gradually increased since the late seventies. At present the largest machines in this category have installed capacities of the order 400 to 500 kW and rotor diameters up to 35-40 m. The main reason for the up-scaling is that power costs so far has been reduced, and secondarily that large-size machines save land and possibly also electrical auxiliary installations. Figure 2 illustrates how the continuous up-scaling has correlated to lower production costs.

Also the reliability of the wind turbines has improved. Figure 3 shows on an annual basis the development in failure probabilities for a wind turbine over the period 1979-1984 (major accidents). It clearly illustrates the improvement obtained in reliability.

The international trend indicates that the machines previously called "small wind turbines" now begin catching up with the large machines resulting from the national research programmes. It is impossible to predict the future development though indications are found. ref. [5] and [6], that - with the present technology and materials - an optimal rotor size exists. Utility experiences from the application of wind power in Denmark seemingly indicates a optimum unit capacity between 300 and 700 kW - typically corresponding to rotor diameters of 25 to 45 m - for land-based turbines organized in clusters, "wind farms". In the case of off-shore location, additional technical problems - like more complex and costly wind turbine foundations and less easy access - tend to favour a larger machine size.

As previously indicated, the efficiency of a wind turbine is evaluated relative to the fraction of kinetic energy extracted from the air flowing through the swept rotor area. The efficiency - or the power coefficient - is not constant for all wind speeds. Designing the wind turbine, it is important that the maximum power coefficient is "placed" at the particular wind speed where most energy is available. The maximum power coefficient itself is a measure of the stage of development of the technology.

Thus, over a period of 15 years, the maximum power coefficient has increased from approx. 30% to 45%, i.e. a relative increase of 50% in efficiency. The present high value of the power coefficient should be seen in the light that first-order theory (Betz-theory) predicts a theoretical maximum of 59%. This large improvement is basically due to improved rotor aerodynamics and reduced losses in transmission and generator.

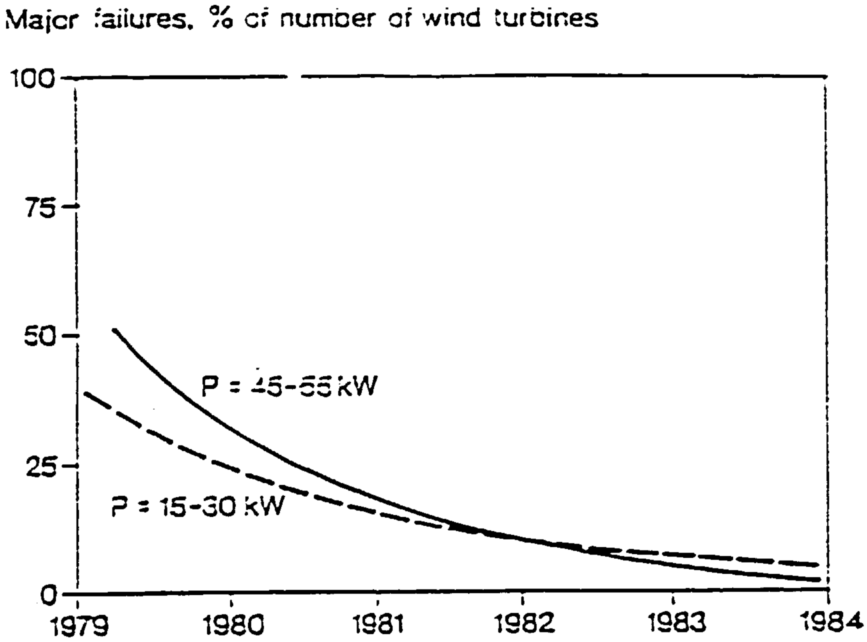

Figure 3. Major failures, in percentage of number of wind turbines; source: Ref. [9].

Table 1. Basic figures of development in wind turbine installations (WT) in Denmark.

PARAMETER	1983	1984	1985	1986	1987	1988	1990
Number of WT-units	500	600	950	1200	1600	1800	2900
Total WT capacity (MW)	19	26	47	74	110	140	340
Total WT production (GWh)	25	33	50	120	160	210	520
Power system production (GWh)	24,600	25,750	27,400	28,600	29,700	29,300	30,000
Wind power share	0.1 %	0.1 %	0.2 %	0.4 %	0.5 %	0.7 %	2.1 %

2.6 Development in the Wind Electricity Production

The development efforts have resulted in a substantial increase of the totally installed wind-power capacity over this decade as indicated in Table 1. The table shows a remarkable increase of installed wind turbine capacity and production in Denmark. Including the 100-MW agreement - described below in further details - wind power production amounted by the end of 1990 to 2.1% of the total electricity production in this country.

Parallel to the installation of wind turbines in Denmark, the manufacturers have managed a considerable export, primarily to the USA. The accumulated export for the years 1982 - 87 thus comprised approx. 7300 wind turbines with an aggregate capacity of 600 MW. Changing tax rules in the States and an unfavorable dollar exchange rates have reduced the export over the last couple of years. The drop in exports to the USA has to some extent, however, been compensated by an increasing export to European and third-world countries. Not reaching the export level of the mid-1980'ies, the total Danish export in 1990 was 80 MW, corresponding to a total value of approximately 80 million US dollar.

2.7 The 100-MW Wind Power Agreement

Following a political initiative in 1985, the Danish Ministry of Energy entered into an agreement with the western and eastern associations of Danish electric utilities, ELSAM and ELKRAFT respectively, concerning increased utilization of renewable and indigenous energy sources in electricity generation.

According to the agreement, the Danish utilities shall install a total of 100-MW wind power capacity during the period 1986-90. Of this amount 45 MW are to be located in eastern Denmark and 55 MW in the western part of the country. This extension roughly corresponds to 30% of the present totally installed wind turbine capacity in

Denmark. The agreement ensures a coherent, major expansion with large-scale wind turbines and wind farms, providing the basis of a further technological development and a more detailed assessment of technical and economic factors associated with large-scale utilization of wind energy.

The programme is financed by the electric utilities. The benefits or losses will relate to the electricity consumers only. This agreement is in line with Danish energy policy and also serves to encourage development of the Danish wind turbine technology. The utility sponsorship of developing MW-size wind turbines does not satisfy the needs of the 100-MW programme, requiring immediate application of reliable, low-cost wind energy. Therefore, the programme is mostly based on medium-size turbines from 100 to 450 kW, now commercially available from wind turbine manufacturers. Such wind turbines take up more space per installed MW, a regrettable consequence, considering the highly intensive utilization of Danish land in general. This is further aggravated because the utilities have difficulties in achieving public acceptance of wind farms. Therefore, off-shore siting is by now not only an option seriously considered: in August 1991 the first Danish - and the first in the world-off-shore wind farm was set into operation. The Vindeby Wind Farm consists of 11 machines of each 450 kW sited 2 km off the coast of the island Lolland in the Baltic sea.

The present 100 MW agreement will be followed by another 100 MW agreement between the utilities and the Government, to be implemented by the end of 1993.

A second category of problems is related to land preservation, bird protection, special scenic qualities etc. Naturally, such problems are carefully considered in the planning process, but nevertheless they are repeatedly referred to with great effect during subsequent public hearings.

Whether similar problems related to public acceptance of wind turbine siting will emerge in other countries will depend on a number of factors such as topography, population density, and distribution, intensity of land use in areas of relevance to utilization of wind energy etc.

3. FEASIBILITY OF THE WIND POWER

True production costs for grid-connected wind power plants depend on a number of parameters, such as actual wind conditions, plant investment, lifetime, interest rate, operation and maintenance costs, annual utilization - and consequences of the wind power plant's interaction with the general power supply system. Due to the low capacity value of wind power, back-up capacity may be needed to maintain supply reliability. And in cases of overflow of wind power production during periods in which priority production in the conventional system covers the demand, the wind energy production may have to be stopped. Comparing wind power with a fossil-fired alternative, the wind power production costs shall be seen together with the total conventional production costs of a new plant including all fixed and variable costs and amortization of the investment, adjusted to allow for a removal of both SO_2 and NO_x

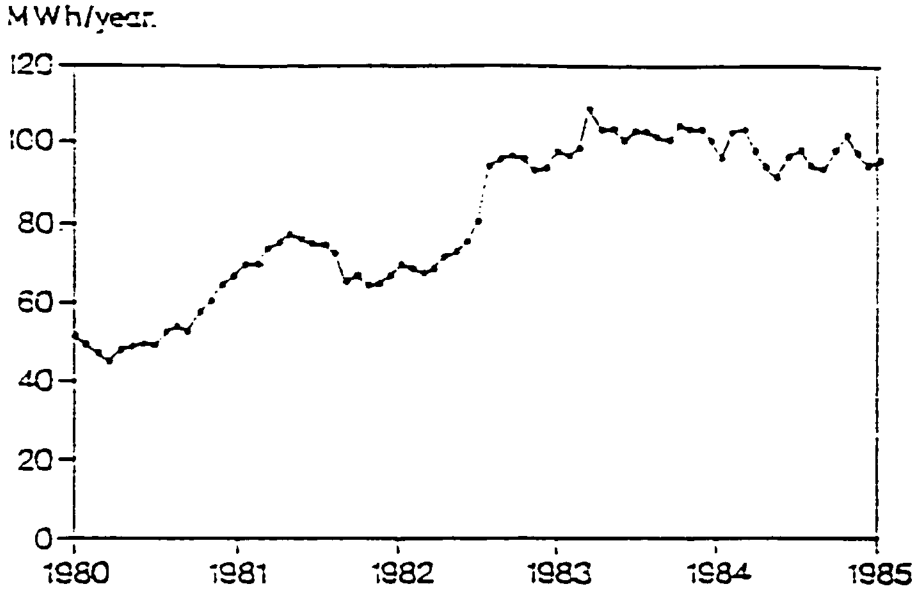

Figure 4. Average annual production (per unit) from the 55-kW wind turbines installed in Denmark as a function of the time of manufacturing. The production figures have been adjusted to "a reference wind year".

The interaction effects become increasingly significant with magnitude of the wind energy component of a supply system. In the example presented in the next section, the wind turbine plant is assumed to be a marginal part of the system without overflow problems. Therefore, only direct costs of the plant are considered, being compared with the displaced fuel and variable operation and maintenance costs.

Increased energy production and increased reliability are two important components in developing the economic performance of the Danish wind turbines. Considering the accumulated annual production of the wind turbine, the reliability of the machine is an important parameter. The failure rate has been reduced to a very low level, ensuring that the machine is available for energy production when the wind is blowing. These improvements in technology and reliability are illustrated in Fig. 4, showing the average production of a large number of 55-kW wind turbines for the year 1986 as a function of the time of manufacturing of each unit. Since 1986 production has increased even further, though not at the same pace.

Over a few years the remarkable improvement in performance can be ascribed mainly to:

* Improved design and production methods.
* Higher towers giving access to higher wind speeds.
* Larger rotor diameter, i.e. larger swept area.
* Improved aerodynamic profile of rotor blades and optimization of rotor speed and blade angle.
* More efficient transmission systems.
* Better wind resource estimation techniques, leading to an improved siting.
* Increased reliability.

Yet another important parameter is the reduction of investment costs, which partly comes from "economy of scale", either from the number of units produced or the size of the units. Clearly, the starting of a mass production of turbines in the early eighties reduced the investment per kW installed (assisted by the large export to California).

From an economic point of view the optimum turbine size has not yet been - and probably never will be - determined but there is a clear evidence that investment per kWh produced tends to decrease with increasing turbine size. The effect is at least to some degree due to a relative cost reduction from increased turbine size. It should be noted, though that the largest turbines are also the most recent and the most optimized designs. Figure 5 shows the investment per kWh produced per year plotted against generator size for different wind turbine types commercially available in Denmark in 1987. It is seen that significant improvement in economy has been achieved by increasing size, and it is not obvious that the minimum cost/kWh has been reached.

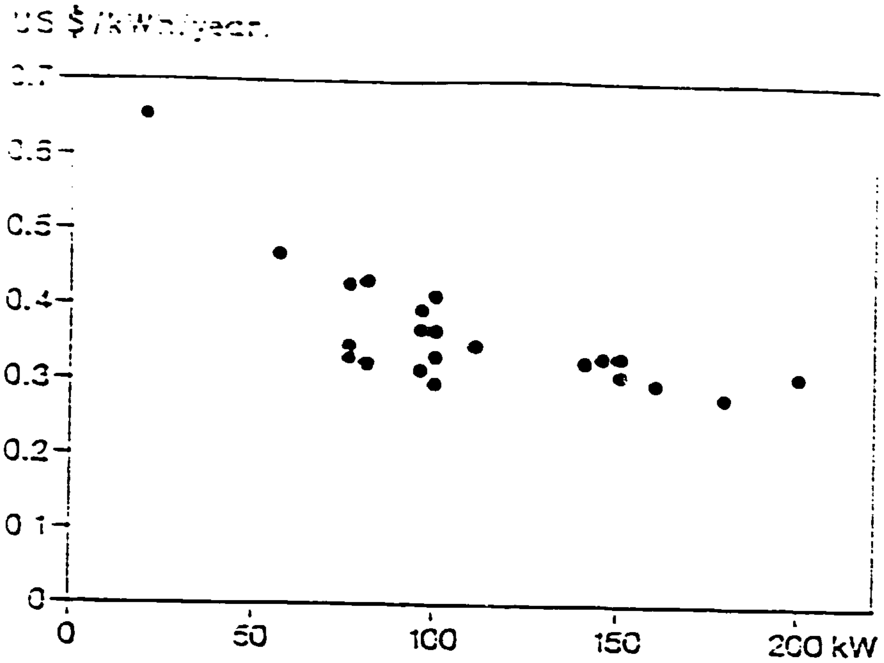

Figure 5. Investment costs per kWh annually produced, for different generator sizes. Source: Ref. [9].

3.2 *Production Cost Sensitivity*

To illustrate the production costs of power from a wind turbine a simple example of the importance of two basic parameters, wind speed and lifetime, is illustrated in Fig. 6 below. The graph shows the production costs in US cents per kWh from a wind turbine as a function of wind speed and under different assumptions concerning the installation lifetime. The figure is an update of a similar figure in ref. [10].

Table 2. Basis assumptions of Fig. 6, exchange rate mid-1989 level.

ITEM	
Overall efficiency:	35 %
Swept area (rotor diam. = 23m):	415 m^2
Price of wind turbine installed.	185.000 US$
O & M costs, in % of total costs:	2%
Discount rate:	7% p.a.
Exchange rate:	7 DKK/US$

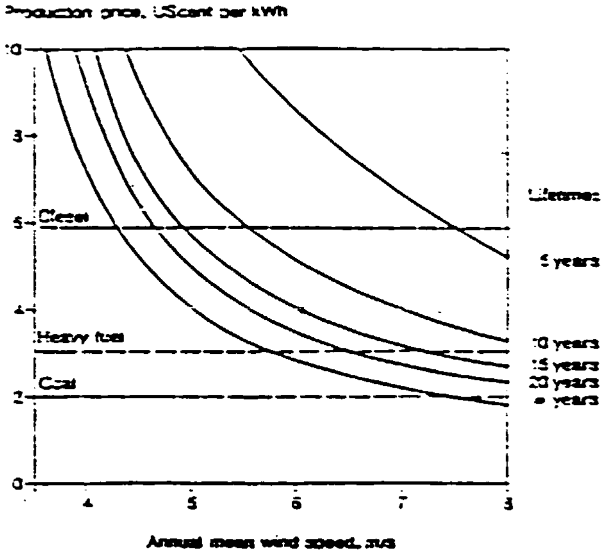

Figure 6. Cost of electricity produced by a wind turbine as a function of annual mean wind speed for different lifetimes expected. Fuel prices mid-1989 level. The overall efficiency of the wind turbine is assumed constant for all wind speeds.

In order to relate the costs to conventional power production, the costs of 1 kWh for fuel, operation, and maintenance are shown for an average Danish thermal power plant based on coal and fuel oil, respectively. These costs are based on a plant efficiency of 40% and represent a first-order approach of avoided costs in the grid, receiving the power produced by a wind turbine. Furthermore, the fuel costs are shown for 1 kWh produced by a (small) diesel powered plant (efficiency 33%).

The immense importance of the wind resources is clearly illustrated by Fig. 6; the lifetime of the machine is important to a certain point, 15-20 years, after which period only the discount rate remains an important parameter. Also, the figure clearly illustrates that deciding upon a wind power plant investment, it is vital that key data are available on the type of "competing" fuel. The example is calculated for a standard type 150-kW wind turbine. The basic assumptions are:

The latest thorough analysis of the production cost, ref. [12], concludes that depending on a number of parameters such as foundation, land and electric cabling costs but foremost the wind energy resources, the cost of producing one kWh by means of a wind turbine is 5 to 7 US-cent.

3.3 Perspectives in the Future Development

A clear trend in the development of Danish wind turbines today is the appearance of large units. For a period the 55-kW type dominated the market. As the technology has matured and production methods have been refined, turbines of 100, 200, 300 and even 450 kW have been developed and put into operation using the same basic principles as in the pioneering 55-kW type. One may expect a further development of the known concept toward a unit size above 450 kW. At the moment the driving force for upscaling is primarily a better land use and a demand for larger units from the utility marked. There is some doubt that larger unit themselves will lead to a reduction in cost. However, with the commercialization of 500 kW turbine and a continued technology development, a cost reduction of 30% is estimated in Denmark.

Due to the restriction in land use, off-shore location of wind power plant may, despite of higher investment costs, be attractive as the wind conditions at sea in general are better than at most in-land sites. As an example the first off-shore wind power plant of 5MW at Vindeby has twice the investment cost of a similar plant on land. However, the energy production is 70% more. The Vindeby plant is the first of its kind, other studies indicate that the investment cost can be reduced to 50% more.

3.4 Future energy policy in Denmark

The framework for the future energy policy in Denmark - and therefore also for the potential development - is the Energy 2000 Action Plan [15]. The reasoning behind the Action Plan is centered almost entirely on environmental and social issues and contains little reference to business related issues. The action plan operates with three development scenarios , used as three different frameworks for the prediction of trends, evaluation of expected problems and estimation of necessary R&D topics. The scenarios are:

Scenario	Installed year 2000	Increase MW/year
Low (supply)	800	46
Medium (economy)	950	61
High (environment)	1350	100

The three scenario's reflect three different priorities:

The Supply Scenario has main emphasis on changes in the supply structure and the use of fuel. This is "the easy" scenario.

The Economy Scenario has social economic considerations as first priority.

The Environment Scenario concentrates the effort on reducing the environmental impact, in particular CO_2 emissions. Therefore it is combined with a high priority on energy savings.

During the years 1988 to 1991 the rate of increase in installed wind power capacity has been a stable 70 to 90 MW/year. This means that even in the "old" energy policy the actual rate of increase was between the economy and the environment scenarios, even after direct subsidy vanished in 1989.

The Energy 2000 Action Plan identifies a number of technological development trends that are considered necessary in order to realize the environment scenario. Examples are:

* More silent wind turbines
* Larger cost/effective wind turbines
* Visual accept of wind turbine clusters
* Economy of wind power
* Commercially viable energy storage systems.

It is envisaged that the economy of wind power might increase by 40 Pct year 2000.

The action plan identifies a number of barriers that may prevent or counteract the desired development. It also lists a number of actions that may ensure the environment scenario in year 2000 within topics such as:

- Grid connection and pay-back rates. Firm predictable rates are necessary for private investors. This means that tariffs must be defined and maintained for 10-15 years.

- Siting possibilities. A new siting investigation for 1500 MW wind is ongoing, and the result will show if existing criteria must be changed in order to secure sufficient space.

- Popular accept of wind turbines. This implies issues of noise, visual impact etc. Honest information to the public on pro's and con's is considered vital.

* Financing of wind turbine. Rules must be established that ensure that wind turbines can be financed in the normal Danish system used to finance and insure property.

* Administration of wind turbine legislation. Specific rules may have to be adjusted to ensure the desired result.

* Wind turbine economy. Comparison of cost/kWh from wind turbines with the cost from traditional supply may be more realistic if more broad social economic considerations - including CO_2 reduction caused by wind turbines - are applied.

These actions would seem entirely realistic and possible in the presence of an energy policy, but it would hardly seem realistic to expect this development based on the normal market mechanisms alone.

4. A GLOBAL VIEW OF WIND ENERGY

4.1 Wind Energy World-wise

Following the oil crisis of the seventies, wind energy research programmes and implementation projects were quickly initiated by governments in several countries, most notably Denmark, the Federal Republic of Germany, the Netherlands, Sweden, the United Kingdom, and the United States of America, and later on many other countries initiated national wind energy programmes.

The initial government projects were soon followed by an industrial effort supported by various subsidy arrangements. The result was an exponential growth of the wind energy industry. From a worldwide totally installed capacity of a few MW in 1980, an estimate by the end of 1990 suggests that more than 20.000 wind turbines with a total capacity of approx 2100 MW operate as grid-connected machines throughout the world. The machines represent an investment of 2-3 billion US $ which shows that the wind energy industry has gained significance.

More than 75% of the machines are found in California, USA, and a major part of the rest in Denmark. The main reason for the dominant position of the USA and Denmark in terms of producing wind turbines is the incentives by the respective governments to use wind energy. Such incentives were needed to counter the industrial and technological immaturity of wind energy. The success of these incentives is shown by the decrease in the actual costs of energy from wind turbines to the order of 5 US cents per kWh on good wind sites, disregarding government subsidy. At such prices wind energy definitely can compete with the most expensive fossil fuel i.e. gas oil.

Also, a large Japanese company has entered the wind turbine market, manufacturing wind turbines for export.

An increasing number of developing countries have shown interest in the utilization of wind energy and initiated programmes for development of national production capabilities and/or import of foreign machines. Likewise the United Nations and a number of foreign aid agencies in the industrialized countries have been requested to engage in wind energy projects.

Unfortunately, it has not been possible to compile a complete list of developing countries interested in wind energy. However, it should be mentioned that the Danish International Aid Agency (DANIDA) has been and/or is engaged in several projects throughout the world, including the Cape Verde Islands, Somalia, India, Egypt, the Peoples' Republic of China and Tanzania. To our knowledge, the United Nations Development Programme, (UNDP), United Nations Food and Agricultural Organization (FAO), United Nations Industrial Development Organization (UNIDO) and the World Bank are investigating/preparing and/or executing projects in the said countries as well as Algeria, Barbados and probably many other countries.

Table 3 gives the leading countries listed in order of installed wind energy capacity. While the USA by far has the largest amount of installed capacity, Denmark has 70 W installed wind energy capacity per capita corresponding to an average power of 15 W and thus with a total average electric power production per capita of approx. 700 W wind energy contributes with 2.1% to the production.

In some developing countries, the energy consumption may be 1/10 or lower than the consumption in Denmark, and if such country managed to produce the same per-capita-installed wind energy capacity (70 W) the wind energy penetration would be 20%!

Table 5. Installed wind energy capacities in the leading countries in the world by the end of 1990, ref. [15].

Country	Installed Capacity (MW)	No. of Wind Turbines	Average Size (kW)	Per Capita Installed (W)
USA Incl. Hawaii	1630	16000	102	5
Denmark	343	2900	118	70
Germany	55	500	110	1
Netherlands	45	450	100	3
India	38	250	152	0
Sweden	12	45	267	2
UK	10	45	222	0
Spain	10	60	167	0
Greece	8	20	400	1
Other	20	160	125	
TOTAL	2171	20430	106	

In most cases the interest has been directed toward the "standard" machines connected to existing electric grids. Since in many cases the power supply in developing countries is based on gas oil, the savings introduced by wind energy power plants are correspondingly higher than in case of coal-fired conventional plants.

Recently, however, several developing countries have shown an increasing interest to participate in the development of systems where power from the wind forms a larger fraction of the total energy supply. Such systems are frequently named hybrid systems or more specifically wind/diesel systems, the basic principles of which will be dealt with in the following.

4.2 Hybrid Systems

With a percentage of power produced by wind turbines comparable to the power from the conventional generators, control problems arise. Especially the problem of keeping the wind turbine generator frequency constant is serious. For the ultimate system, where the wind turbines and conventional generators can operate independently, new system units must be added in order to ensure power quality and continuity of supply. Figure 7 shows the general principles of a wind/diesel system designed for operating the wind turbine(s) also with the diesel generator disconnected. Basically, an independent operation of the wind turbine is made possible by the battery storage to which access is made by the rectifier and inverter (converting from AC to DC and vice versa), and by the dump load which simply dissipates excess energy. The flywheel is installed to stabilize the system frequency and to ensure a fast start-up of the diesel. The advantage of the wind/diesel system is that it can operate independent of diesel supply, at least for periods of time, and with a possible better utilization of the wind turbine capacity.

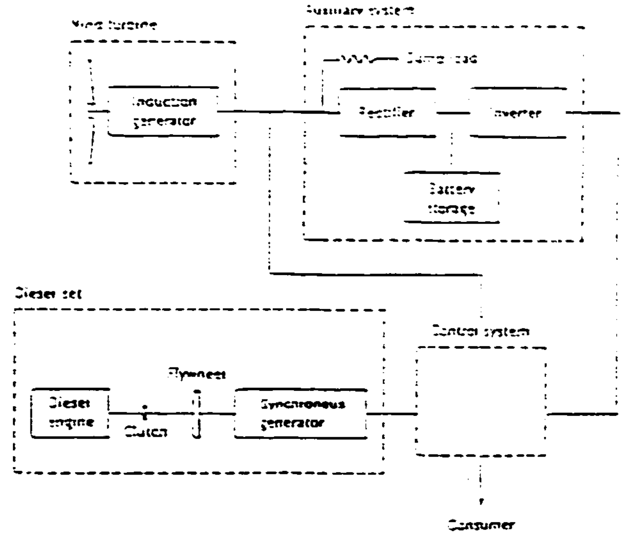

Figure 7. A diagram showing the basic components of a full-scale wind/diesel system.

Moreover, many developing countries will often find it difficult to cover high running costs and will therefore encourage operational strategies minimizing the fuel consumption. Such strategies may end up being complicated but provide, on the other hand, a wider range of possible solutions of system design and configuration.

For example, when batteries are used, the system may be arranged so that the wind turbine can supply power directly to the grid; any surplus energy will charge the batteries. If the batteries are fully charged, surplus power is dumped. If the wind power is insufficient for a grid supply the grid, and the batteries are sufficiently charged, the wind and batteries together can supply the grid. If the wind turbine and/or battery storage are unable to provide the necessary power, the diesel set will have to be started up, in which case any power produced by the wind turbine will be used for battery charging or direct grid supply. Strategies other than those simply aimed at stopping the diesel for the longest possible unbroken periods can be applied: power produced by renewable sources feeds the grid directly to minimize losses in batteries and dump load, assuming that losses in the diesel set(s) remain low, or batteries are kept fully charged whenever convenient in order to meet peak load demand or in order for the power plant to be able to shut down the diesel engine in a certain period.

If a wind/diesel system is installed in a rural community with no previous electric supply, it will dramatically change the community's possibilities of industry, water supply and irrigation, cooling of food and medicine, lighting, and so on. A significant part of the return of such an investment is the development of the social possibilities which are difficult to evaluate in economic terms.

A more thorough description of the principles is found in Refs. [7] and [11], while Ref. [14] gives a status for the technology development of wind-diesel systems in Denmark.

4.3 Economic Viability of Hybrid Systems

As demonstrated in Section 3, wind resources play an extremely important role in the economic viability of a wind energy project. Also when dealing with wind/diesel systems the available wind resources will be of major importance and thus a key item when deciding whether or not to implement a project. The cost of the system itself (wind turbine, control system, storage etc.) is very difficult to quantify, since no wind/diesel system - notably with a convincing record of operation - seems to be commercially available at present.

It is evident, however, that the mere extra costs related to hardware - the inverter (conversion from DC to AC current), control system and possibly a battery storage - will increase the energy price considerably compared to the grid-connected concept. Depending on the detailed choice of system configuration and based on the same wind regime, the kWh-costs may be evaluated a 100% higher. The obvious question is therefore: why go through all the trouble with an extended control system if the costs are deemed to increase anyway?

Practical experiences show that in remote areas with isolated, small communities, there are several reasons for learning to deal with the extended complexity of the wind/diesel system and the additional costs:

- In remote areas or small island communities, the fuel prices may easily be a factor of 2 or 3 higher than in more accessible locations.
- In remote areas, the fuel supply reliability may be fragile: therefore, the employment of a wind/diesel system will increase the power supply reliability.
- With less diesel oil consumption, the air pollution will be reduced.
- Deforestation may be reduced using wind-generated electricity for cooking instead of wood.
- Local involvement in plant operation improves the reliability of local power supply.

Finally, it should be stressed that innovations may be expected to considerably affect the costs of energy from hybrid systems; especially less expensive inverter equipment and storage units would bring down costs.

4.4 Wind Turbine Siting

The success of the Wind Atlas Method was recognized by the European Community's Directorate-General for Science, Research and Development, DG-XII, which for a number of years has funded the development of a European Wind Atlas . The development work has been headed by Risø National Laboratory with participation from the member countries of the European Community (EC).

A large numbers of climatological data from all the EC countries have been analyzed, using Wasp, the Wind Atlas Analysis and Application Programme developed for the European Wind Atlas. The result is a catalogue of generalized wind climatological information for European countries, and by means of the programme it is possible to compute the wind speed distribution at a site selected for erecting a wind turbine. Apart from the European Wind Atlas the Wasp code is currently used to establish wind atlases and investigate wind energy resources in more than 50 countries all over the world.

The Wasp code has a built-in facility for modelling the air flow in a complicated terrain as found in the more mountainous areas of Europe. The flow model facilitates the "translation" of wind measurements made at one location to a nearby wind turbine site.

The European Wind Atlas project was finalized in 1989, and it is expected that the results from the work will have a significant impact on the utilization of wind energy as power supply possibility in Europe.

The concept of a Wind Atlas and the use of the wind atlas methodology has received great acceptance internationally. In addition to Europe, wind atlases have been or are being prepared in countries such as Sweden, Finland, Algeria, Jordan, Syria and Turkey.

In addition the wind atlas method has been used by Risø to predict wind conditions in USA, Australia, Chile, China, India, Somalia and others.

5. CONCLUSION

During the last decade wind turbine manufacturing has undergone a very substantial technological maturing process. During this process the conversion of wind energy into electricity has developed to a technological level where - under certain conditions relating to the wind conditions and the penetration in the energy system - it is economically competitive compared with a thermal production of electricity.

The most important achievements within this development are related to improvements in design and production of wind turbines and more accurate techniques for wind resource estimation. This leads to increased reliability and aerodynamic efficiency (power coefficient), which in turn increases the annual electricity production. Thus, the average annual production in Denmark from a 55-kW turbine manufactured today is twice the level of a 1980-turbine.

Hybrid systems, i.e. wind/diesel systems, are still in the developing phase. Such systems seem especially appropriate for electricity supply to local grids in communities with no connection to a general supply system. Under such circumstances the alternative will often be a power production based on high-cost fuel, i.e. diesel oil (gas oil). Here, wind/diesel systems have advantages as regards fuel saving and local industrial engagement aspects. This applies to industrialized as well as developing countries.

Experiences in Denmark and elsewhere clearly demonstrate the importance of having access to a wind turbine test center. Such a center strongly supports the technological development, the manufacturing and practical implementation of wind turbines in a local area in many ways, e.g. by accumulating technical and production related data, by issuing system approval certificates, by providing consultancy services to wind turbine manufacturers, wind turbine operational staff, decision makers, etc.

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