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Review of Historical and Modern Utilization of Wind Power

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Content

INTRODUCTION

The aim of this paper is to give an overview of the history of wind power, an update on modern utilization of wind power, and an overview of the key literature in the area. During the recent years the history of wind power has been the object for many studies, and it is not the aim of this paper to add anything new to this history

In the literature several words are used, such as windmill and wind turbines. The word windmill indicates that wind power primarily has been used for grinding grain. The word mill is derived from the Latin word for a machine used for grinding grain: molina. Though most European languages do have a separate word for such a machine, kværn in Danish, one also find derivations of molina in many European languages today - French: moulin, German: mühle, Danish: mølle, English: mill, etc. This word is used for both a grinding machine and for machines driven by wind or water used for other purposes - normally referred to as windmills and watermills.

In modern time the term wind turbine is generally used in English. Turbine is derived from the Latin word for spinning top and whirlwind: turbo. In professional engineering literature one also use the abbreviation WECS - Wind Energy Conversion Systems. To co-ordinate the many terms derived from ancient Teutonic and Latin and modern technical terms used in wind power engineering a standard set of terms is recommended (Elliot, 1987).

The History of Wind Power

The technology of transforming the kinetic energy of the wind into useful mechanical power has been applied by man since antiquity. Wind energy is, together with energy from streaming water utilized by a water wheel, the oldest source of power applied by mankind, but we have only solid historical evidence that the energy of wind has been utilized this way for at least one thousand years.

The use of wind power is said to have its origin in the Asian civilizations of China, Tibet, India, Afghanistan, and Persia. The first written evidence for the use of wind turbines are that of Hero of Alexandria, who in the third or second century BC described a simple horizontal-axis wind turbine. It was described as giving power to an organ, but it has been discussed whether it was of any practical use apart from being a kind of toy. From more solid evidence we know that in the 7'th century B.C. the Persians seriously used wind power from a vertical-axis machine.

From Asia the use of wind power spread to Europe through civilization. From contemporary sources we know that windmills have been used in the 11'th or 12'th century in England. Also from a contemporary eyewitness (1190) we know that German crusaders brought the skills of building windmills to Syria. From this, we may assume that this technology was generally known all over Europe since the Middle Ages.

The windmill and the water wheel were, and still are in many less developed parts of the world, used for simple low energy processes such as water pumping and grain grinding. Since the first descriptions of windmills the technique developed over the centuries with some variations from place to place. We all know the famous Dutch windmills used for water pumping, and in the Mediterranean area several islands are known for their old picturesque windmills.

With the introduction of the steam engine in the 18'th century the world gradually changed its demand for power to techniques and machines based on thermodynamic processes. Especially with the introduction of fossil fuel (coal, oil and gas) the advantages of these machines became obvious. Firstly, steam engines, steam and gas turbines and oil and gas based engines are much more compact and can provide power at a much larger scale than necessary for water pumping and grinding. Secondly, they can be located independent of the streaming water or good wind sites. Finally, these new machines provided a more reliable source of power than wind turbines.

Therefore, the importance of wind energy as a power source decreased during the 19'th century and especially during the present century. Though, in some parts of the world wind energy prolonged its utility. In countries with populations scattered over large areas, such as the Americas, Australia, and Russia/USSR wind power continued to contribute to the power needed by for example farming. The American Jacobs brothers produced from 1925 to 1957 battery charging wind turbines in the range of 2.5 and 3 kW in large numbers, and by the middle of this century The Aermotor Company of Chicago claimed to have 800,000 windmills in service - mostly for water pumping. These machines were built since the end of the 1890's and were made by steel.

With the electrification of the industrialized world, the role of wind power decreased. Fossil fuels showed to be more competitive in providing electrical power on large scales.

Research in and construction of wind turbines continued to a wider extent than normally assumed. Today many people assume that the interest and research in wind power vanished due to the tough competition from the fossil energy sources. This is not true. All over the world theorists and practicians continued to design and construct electricity producing wind turbines. Some of the highlights are the turbines of the two Danes P. la Cour (around the turn of the century) and J. Juul (after World War II). In America the famous 1250 kW Smith-Putnam wind turbine was erected at a place in Vermont called Granpa's Knob.

Meanwhile the traditional windrose - the multibladed wind turbine used in the farmland all over the world - was still further developed and refined. The wood used in most parts of these machines was replaced by iron and steel. Lattice steel towers were introduced and even steel blades came into use. This transformation from wood to steel did not appear over night but went on for some decades, and contributed to the optimization of the wind turbines. As mentioned the Aermotor was one of first wind turbines totally built of steel.

In the 1920's and 30's the French F. M. Darrieus and the Finnish S. J. Savonius designed and tested new concepts for VAWT machines. In the 1980's the Canadian firm Flowind mass produced a turbine of the Darrieus concept. These Darrieus turbines are now a significant element in the Californian wind farms.

Also the research work continued. La Cour made some path-breaking empirical observations around the turn of the century by using a primitive wind tunnel. In the 20's the German professor Albert Betz of the German aerodynamical research center in Göttingen made some path-breaking theoretical studies on wind turbines in the light of (for that time) modern research. Also in the 1920's H. Glauert contributed with an aerodynamic theory for wind turbines. Both of these theoretical contributions are still the foundation of today's rotor theory.

In the late 1930's the young Austrian engineer Ulrich Hütter worked as a chief engineer at the state owned Ventimotor wind turbine firm in Weimar outside Berlin. In 1942 he obtained his doctoral degree from the university in Vienna on a theoretical study on wind turbines. In the 1970's he was called upon again to lead a governmental (FRG) research effort in wind power techniques.

In 1948 Palmer C. Putnam - the man behind the wind turbine at Granpa's Knob - issued a textbook on wind energy, which is now a classic. Putnam's colleague on the Granpa's Knob Project Percy H. Thomas was also in the forties very active within this field. In 1955 another American E. W. Golding issued a textbook with the title "The Generation of Electricity by Wind Power", and it is still widely used in new editions.

Also in the USSR research in and production of electricity producing wind turbines continued. In the 1950's E. M. Fateyev published a number of titles of which at least one is translated into English by NASA, and widely referred to.

A UNESCO conference on wind and solar energy was held in New Delhi in October 1954, and a World Power Conference was held in Brazil in July 1954 (Golding, 1976). In 1961 a "United Nations Conference on New Sources of Energy" was held in Rome. The proceedings from this conference was published in 1964, and it contains key sources of information of the international development in wind power utilization in the first half of this century.

Hence, research in wind power utilization did not die due to the competition of fossil fuels, and the revival of the wider interest in wind power after the 1970's did not start from scratch, but could build on a solid foundation of theories and practical experiences.

Above we mentioned the transition from wood to steel as the most dominant material. When the new era of wind energy was initiated in the 1970's new materials and technologies were available. Composite materials such as fibreglass showed to be very suitable for the blades, and electronics were developed to control the wind turbine.

Wind Power in Denmark

The early dissemination of windmills all over Europe also involved Denmark. Here the first windmill was mentioned in 1259, and it was placed in the village of Fløng between Roskilde and Copenhagen (Holst, 1923, p52). With the fossil fuels and the electrification the development followed the same pattern as in the rest of Europe, but in countries without any domestic fossil resources such as Denmark, wind energy continued to contribute to the supply of energy. First of all with the classical purposes in the farm land as pumping water and grinding grain. In 1916 alone, 1300 new ones were built to provide power to threshing machines, grinding mills, water pumping, (Juul, 1964).

The modern wind energy utilization in Denmark and at Risø build on a more than 100 hundred year old tradition of meteorology and wind turbine research and development in Denmark. This tradition comprises cutting edge research, close relations between scientific research and industrial utilization of the results, and international cooperation.

With no other realized natural energy sources (no water falls for hydro power, no coal, etc.) it may seem natural that Denmark became the first country in which scientists and engineers began a dedicated effort to implement wind technology as a basis for electrification. This started in 1891, when Poul la Cour ("the Danish Edison") and a team of scientists built a test windmill, funded by the Danish government at Askov Folk High School. La Cour was drawing on the results of two contemporary Danish engineers and scientists H. C. Vogt and J. Irminger, who together with the American P. S. Langley participated in formulating modern theory on aerodynamic lift and drag.

By 1918, as a result of la Cour's work, a fourth (120) of all Danish rural power stations used wind turbines for power generation. Most machines had a rated capacity of 20-35 kW. After the war with a sufficient supply of fossil fuel, these machines were rapidly outdated, and in 1920 only 75 turbines were left. (Arnfred, 1964; Shephard, 1990).

Towards the end of the interwar period and during World War II Danish industrial wind power developments were undertaken especially by the companies Lykkegaard Ltd. and F. L. Smidth & Co. By 1943 Lykkegaard had installed 90 machines; typically 30 kW machines. F. L. Smidth & Co. developed two machines: a 2-bladed 60 kW machine and a 3-bladed 70 kW machine. 21 of these were installed during World War II.

After World War II, J. Juul, a Danish engineer at a power utility, SEAS, started an R&D programme on wind energy utilization. This R&D effort formed the basis for Juul's design of a modern electricity producing wind turbine - the well-known 200 kW Gedser machine. The Gedser machine was installed in 1959 and was in operation until 1967.

The awakening green movement in the Western societies and especially the oil embargoes of 1973 and 1979 sat the stage for the present era of wind power, and a governmental committment to the development of wind power in Denmark has continued more or less undisturbed ever since. Although the governmental financial support to wind power has been questioned, especially from the traditional industrial society, after the stabilizing of fossil fuel prizes during the 1980's.

In 1977, when data for large wind turbines were badly needed, the refurbished Gedser machine was used for a measurement programme, which was co-funded by the US Department of Energy. This programme was carried out by Risø National Laboratory and formed Risø's entrance to wind turbine R&D. Besides a tradition in wind turbine R&D, Risø also draw on a tradition on boundary layer meteorology and wind climate studies. The studies of aerodynamics and wind tunnel experiments performed by Irminger by the turn of the century was continued at the Technical University of Denmark by Professor Nøkketved, Martin Jensen and Niels Franck. Their pathbreaking research on wind climate, model laws, terrain roughness, and shelter effects formed the scientific platform for Risø's work on the Danish Wind Atlas and the European Wind Atlas used for wind resource estimation. This work was initiated in the late 1970's. But as early as in 1968 Risø participated in the so-called Kansas Experiment where the present, basic formalism in the description of surface-layer turbulence was finally established.

Today the Danish government has committed itself to wind power. By 2005 10% of Denmark's electricity consumption is planned to come from wind power. This equals to 1500 MW of installed capacity. 4000 MW of installed wind power capacity has been mentioned as a goal by 2020.

APPLICATIONS OF WIND POWER

Historically, the power from wind turbines historically has been used as a direct shaft power. The rotor axle was directly connected (though, through a gearing ratio) to the mill stone at the old windmills.

Today the output power from wind turbines can be utilized in two ways. Either by direct use of the mechanical shaft power (through a gearing ratio, though) or by letting the wind turbine power an electrical generator, and then utilize the power as electrical power.

Traditionally only the mechanical shaft power was available. During the 18'th and 19'th century windmills all over Europe and the New World were giving power to all sorts of farming and light industrial processes. Windmill-powered machines such as grinding mills, water pumps, threshing machines, saw mills, sugar cane refineries, etc. Today wind turbines are widely used for water pumping all over the world.

One problem by using the mechanical shaft power is of course that the wind turbine has to be close to the place of the machine used. By letting the wind turbine drive an electrical generator one can transfer the power over quite a large distance to the final utilization. Then the electricity can give power to an electrical motor, which gives power to the all the above mentioned classical applications.

Besides these classical applications electricity producing wind turbines are today used in hybrid systems, together with for example a generator driven by diesel. These so-called wind-diesel systems are very suitable in thin populated areas of the world or other areas where electrification is not yet fully implemented. The advantage of wind-diesel systems is that the investment in the wind turbine can be paid by the fuel saved for the diesel generator. Hybrid systems can also contain a fly-wheel storage, photo-voltage devices, water-turbines, battery charging, etc.

Very small wind turbines (less than 5 kW) are widely used for battery charging at remote telecommunication stations - for example in the republic of Mongolia and in Arctic areas such as Greenland. Also yachts often have a very small (less than 1 kW) wind turbine for battery charging. The power can be used for TV sets, communication systems and small refrigerators.

The electrical power also has other and more modern applications, such as domestic heating and light. Already, hundred year ago Paul la Cour used the electrical power form Askov High School's wind turbine for electrolysis producing oxygen and hydrogen which were stored. Oxygen and hydrogen were then led through pipes to the final consumption as fuel for illumination of a great part of the school. This system operated for several years before the turn of the century at Askov High School.

Finally an electricity producing wind turbine can of course be connected to the grid, and here supply the grid with power like other power plants fueled by coal, oil or nuclear power. This application is the most common for today's wind turbines.

WIND POWER UTILIZATION TODAY

By the end of 1996 a total of 6200 MW grid connected wind turbine capacity was installed around the world. In 1996 1200 MW were added. With an approximate cost of 1 MECU per MW of installed wind power, the world market in 1995 has a value of 1300 million ECU. The world-wide annually added capacity of wind turbines (the world market) is rapidly increasing; and is expected to increase to 2000 MW/year by year 2000.

Present world-wide annual installation of small battery chargers is probably in the order of 30 to 50,000 units per year of which 90% (in number) are under 100 W rated power. The main producers of small battery chargers are in the UK (marine and caravan leisure markets) and China (for semi-nomadic cattle breeders in the Mongolian region).

The main application for mechanical farm wind pumps is drinking water supply. The markets for this type of machines include USA, Argentina, South Africa and New Zealand. The present annual installation of wind pumps is probably in the range of 5,000 to 10,000 units.

Reasons for Wind Power Utilization Today

Wind energy today is competitive at specific sites with favorable wind regimes, as can be found in many places, e.g. China.

International organizations such as the International Energy Agency 's CADDET-organization and the International Atomic Energy Association, expect wind energy to be economically fully competitive to fossil and nuclear based power production within the next 10 to 15 years.

Wind energy is clean and safe. Wind turbines do not produce green house gases, as fossil fueled electricity production. Wind energy has very low external and social costs. Wind energy has no liabilities related to decommissioning of obsolete plants, such as nuclear power. The energy invested in the production of a typical wind turbine has a "pay back" time (energy balance) of less than half a year of operation. The environmental impact of wind energy on the environment has been investigated thoroughly in both Europe and America. First of all the noise emission has been discussed, and especially in the late 1980's noise became a crucial issue. Also the sun's reflection in the fiberglass blades has been an important issue, but that has been solved in the early year. Still, wind turbines must be designed and constructed to fit into the landscape. Wind turbines disturbance of birds has been investigated carefully during the recent years. Studies in the United States, Germany, the Netherlands, Denmark and the UK conclude, that wind turbines do not pose any substantial threat to birds.

Wind energy is a domestic source of energy. Wind energy and other renewable energy sources can improve a nations degree of self-sufficiency.

Wind turbines can be installed fast. Wind power plants of, e.g. 50 MW, can be in operation in less than a year from signing the contract.

Wind turbines can be used competitively as a dispersed energy production technology in areas with dispersed electricity consumption.

Wind energy is a popular source of energy. Opinion surveys indicates, that the majority of citizens in most European countries in general favours renewable energy sources such as wind power. Opinion surveys in areas of Denmark and UK with wind farms indicate that 70 to 80 % of the population is "general supportive" or "unconcerned" with respect to the turbines.

Wind power is not only applicable in the industrialized areas and countries, but is an ideal technology for the electrification of rapidly industrializing countries. Wind power application can include all types of systems: grid connected wind farms, hybrid energy systems, and stand-alone applications such as battery chargers. Wind power has proved to be a reliable technology adequate both to fuel, and small remote grids and special applications such as desalination as well as large grids. It is modular, more power can be added quickly as the demand increases and it is a cost effective technology in many developing areas and nations. Finally, the technological complexity of operating and maintaining wind turbines do not differ from that of other electrical machines in rural, developing communities: desalination plants, water pumps, etc. Consequently, today wind power is being included in the energy planning of the rapidly industrializing nations in, e.g. Asia.

Wind power alone cannot satisfy the world's increasing demand for electrical power. But wind energy represents a feasible supplement in a diversified energy supply portfolio.

WIND POWER TECHNOLOGY

Modern wind turbine technology

Wind turbine technology can be grouped in three applications:

- Large grid connected wind turbines
- Hybrid energy systems combining intermediate size wind turbines with other energy sources such as photovoltaics, hydro and diesel and/or storage used in small remote grids or for special applications such as water pumping, battery charging or desalination.
- Small "stand-alone" wind turbines for water pumping, battery charging, heating, etc.

Large grid connected turbines encounter for, by large, the biggest market volume, and the technology related to these machines is becoming mature. The size of commercially available grid connected wind turbines has evolved from 50 kW the early 1980's to 500 to 800 kW today. The next generation of commercial machines in the 1000 - 1500 kW size are scheduled to reach the market in 1997.

Today grid connected wind turbines are often placed in wind farms of 10 MW to 100 MW, which is operated as a single plant. Many different design concepts are in use, the most used at present being three-bladed, stall or pitch regulated, horizontal axis machines operating at near-fixed rotational speed. Other concepts present promising advantages, such as gearless designs and variable rotor speed designs.

Modern wind turbines are reliable with a technical availability of typically 98-99 %.

The technology and software for evaluating the available wind resource is now available. In several regions of the world specific evaluations of resources have been carried out. Siting software is now being employed on a regular basis identifying the most energetic wind turbine sites.

It is estimated at present that a penetration (supply fraction) of wind energy on a large grid can be as much as 15-20 % without special precautions being taken with respect to power quality and grid stability.

Concepts

Generally two types of wind turbines can be constructed, named after the direction of their main shaft. Horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). As we saw earlier, these two types have been used since Antiquity.

Three concepts of VAWTs can be seen: the Gyro-turbine, the Savonius-turbine and the Darrieus-turbine. Only the latter has been in serious industrial production. The principle of the Savonius concept is widely used for ventilators. A gyro type wind turbine was briefly produced in Denmark in the 1970's.

Today, only a very small fraction of wind turbines in operation is of the VAWT type.

Hence, the major interest is concentrating on the HAWT types. A variety of these are still in production. The HAWT turbines can roughly be classified in five technical characteristics.

First, the rotor can be placed upwind or downwind.

Second, the number of blades can be any number from 1 and up. For instance the Italian Riva Calzoni turbine and some of MBB's turbines are equipped with only one blade. The traditional wind rose on the other hand do have many blades - 15 or more.

Third, the output regulation provides that the generator does not produce more power than designed for. Three techniques are common. Stall regulation exploits an aerodynamical phenomenon. Increasing wind speed will cause increased output but only up to a certain limit, where - theoretically - the output will be stable independent of increasing wind speed. Using pitch regulation the blades turn round their longitudinal axis so that the aerodynamical characteristics of the blade - and the rotor - can be controlled. Finally the whole rotor can be yawed out of the wind. That isturning the whole rotor plane so that it is parallel with the wind direction.

Fourth, the hub can be connected to the rotor in two ways. It can either be a rigid bolted connection or a hinged connection - a so-called teetering hub.

Fifth, the rotational speed of the rotor can be either fixed relative to the frequency of the grid or it can be variable and the frequency can be controlled by power electronics. For machines not connected to a grid (e.g. water pumping Wind roses) variations in the rotational speed is less important.

COST OF WIND ENERGY

Today wind energy is competitive (in a narrow economical sense) at specific sites with favourable conditions, as remarked in the Commission's Green Paper "For a European Union Energy Policy". If external/social costs are included, it is estimated that wind power in many countries is already competitive with fossil and nuclear power.

Several international organisations without preference for wind power estimate that wind power in a near-term time frame (2005 to 2010) will be competitive with fossil and nuclear power in a narrow economical sense, without taking into account the competitive advantage of wind power on external or social costs.

Ex works cost of wind turbines has decreased significantly with the latest 600 generation kW (40 - 44 meter rotor diameter). For new 600 kW machines the ex works cost is 1.02 million DM in Germany (895 ECU/kW) and 3.06 million DKK in Denmark (699 ECU/kW). The higher ex works cost level for Germany reflects higher towers and different price structures on the two markets.

Project preparation cost depends heavily on local circumstances, such as condition of the soil, road conditions, proximity to electrical grid substations, etc. As a rule of thumb project preparation costs on flat on-shore sites can be estimated to 33% of ex works turbine costs.

Operation and maintenance costs include service, consumables, repair, insurance, administration, lease of site, etc. The annual operation and maintenance cost is often estimated as 3% of a wind turbine's ex works cost.

Technical life time or design life time for European machines is typically 20 years. Individual components are to be replaced or renewed in a shorter interval. Consumables such as oil in gearbox, braking clutches, etc. are often replaced with intervals of 1 to 3 years. Parts of the yaw system are replaced in intervals of 5 years. Vital components exposed to fatigue loads such as main bearings, bearings in gearbox and generator are foreseen to be replaced halfway through the total design life time.

Denmark	Germany	
Ex works cost	3.06 MDKK	1.02 MDM
Total cost in % of ex works costs	1.33 %	1.33 %
Annual O&M in % of ex works cost	3 %	3 %
Average production	1350 MWh	1300 MWh
Interest rate	5%	5%
Amortisation period	20 years	20 years
LPC in local currency	0.31 DKK/kWh	0.11 DM/kWh
LPC in ECUcent	4.2 ECUcent/kWh	5.8 ECUcent/kWh
LPC in (1991) UScent	4.1 UScent/kWh	5.6 UScent/kWh

Table 1. Cost of wind energy in Denmark and Germany.

The average annual wind speed on the site is of paramount importance to the cost of energy. As a rule of thumb the wind turbines' power increases with the wind speed to the third power and thus the cost of energy decreases accordingly. For new 600 kW machines in Germany the average production in 1995 was 1300 MWh (Durstewitz et al, 1996). In 1995 new machines in Denmark (mostly 500 kW and 600 kW) were in average placed in roughness class 1.16 (Energi&Miljødata, 1996). For a 600 kW this means an average production of 1350 MWh annually.

The leveled cost of wind energy (from large wind turbines) can now easily be calculated, as can be seen in table 1.

Cost of energy (in ECUcent/kWh) from small turbines (less than 50 kW) in stand-alone or hybrid systems is typically two to four times higher than for large grid connected turbines. Nevertheless such machines can be a competitive energy source in remote areas, due to high local transportation cost of alternative fuel (commonly diesel). The performance/ economy gab between such small machines and large commercial 250 kW to 1500 kW machines is expected to be narrowed in (but does not vanish) over the next five years - depending on the volume of the market for small turbines.

To compare the figures (for large wind turbines) with those of other electricity producing technologies is quite difficult. For fossil fuel based technologies we need to add the value of environmental costs and for wind power we need to add the cost for power backup.

Today the best way is to use OECD's estimates for new electricity producing plants (OECD, 1993). We can then compare the technologies in a narrow economical sense - without environmental and power backup costs. Comparisons can be made then deflate the wind cost figures to 1991 values and use the exchange rates of 1991 (1st July 1991). Deflation factor: 0.93; 1 USD = 6.98 DKK = 1.81 DM. The average Danish and German figures can then be compared with production costs from the OECD survey - see figure 1.

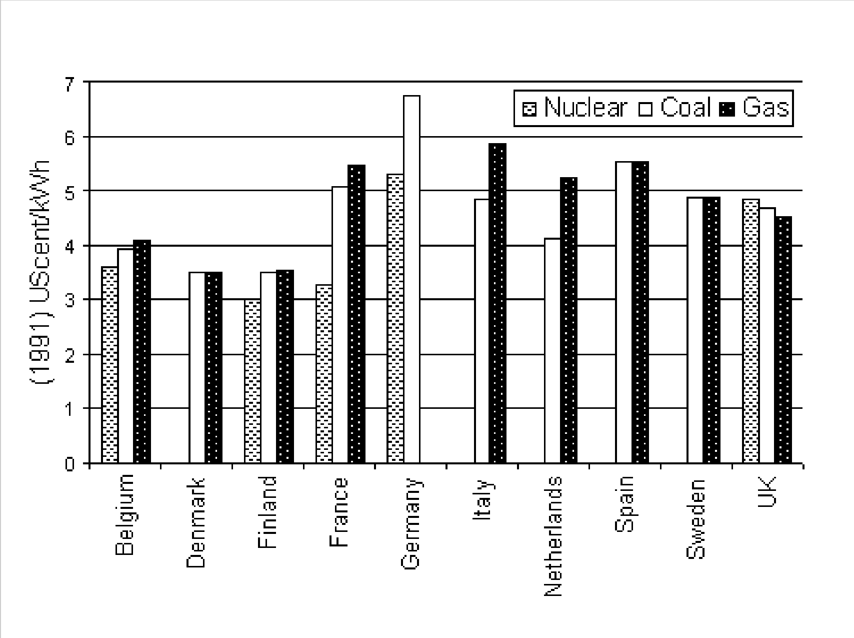

Figure 1. Cost of Electricity in (1991) UScent/kWh for selected European countries. Source: OECD, 1993. For comparison: Average new wind power in Germany 5.6 UScent/kWh, Denmark 4.1 UScent/kWh (1991 price level).

TYPES OF OWNERSHIP

There are three well defined types of ownership for grid-connected wind turbines in industrialized countries. The first and most common is that a group of people (in a cooperative) together buy a turbine and each finances a share equivalent to their electricity consumption. The rest of the project is financed by loan in a bank or a credit association (in UK known as a building society) with the turbine as collateral for the loan. The electricity is then sold to the utility, which by agreement with the government are obliged to buy it at a certain price. This way is in good accordance with the traditional way of organizing and financing such projects used in rural areas of Denmark, where co-operations (in Danish *"andelsselskaber"*) traditionally are widely used. The second way is wind turbines owned by individuals. (e.g. farmers who have windy fields). Finally, the wind turbines can be bought by a utility and installed in clusters - so-called *wind farms*. Common for the three of them is, that the turbine is grid connected and the power is sold to a power utility company.

Two elements were used to create a market for wind turbines in Denmark. The first element was to give the private buyers of turbines a start-up subsidy. From the introduction in 1979 is was 30 % of the total cost. The subsidy was then gradually decreased until it vanished in 1989. The second element was to force the utilities to buy the electrical power at a certain price. The same two elements have also been applied in California.

ENVIRONMENTAL ASPECTS OF WIND POWER UTILISATION

Opinion surveys in areas of the European Union with wind farms or many wind turbines (such as Denmark and UK) indicate that 70 to 80 % of the population is "generally supportive" or "unconcerned" with respect to the wind turbines in their neighbourhood. In a referendum in a Danish municipality with a very large number of wind turbines, 77 % of the votes favoured even more machines.

The political debate is often quite polarised. On the one hand, in many countries the public in general favours renewable energy sources such as wind power. On the other hand, deploying a wind farm in a local community sometimes raises local resistance due to the neighbours' uncertainty and negative expectations about the wind turbines. The public concern is often about environmental effects of wind power such as visual intrusion, impact on birds and birds' habitat, acoustic noise emission, safety, moving shadows, etc. This has been called the NIMBY (Not-In-My-Back-Yard) dilemma.

In industrialised countries public acceptance of wind power is often the most important planning restriction and consequently also a political issue (Elliot, 1994). Experience in developing countries is still limited, but recent large-scale applications in India and China show both reliable production and a high degree of public acceptance along with private sector participation (Andersen, Jensen, Beurskens, 1995).

The public concern is rooted in the fact that the environmental advantages of wind power is on a global or national level, whereas, the environmental disadvantages of wind power is on a local or neighbourhood level, associated with the presence and operation of wind turbines.

Environmental advantages on a global or national level include:

- No direct atmospheric emissions
- No liabilities after decommissioning
- Good energy balance
- Limited use of land

Environmental disadvantages on a local or neighbourhood level, include:

- Noise emission
- Visual impact on landscape
- Moving shadows
- Erosion
- Impact on birds
- Interference with electromagnetic communication
- Personelle safety

Some of these disadvantages are of very limited significance. Quantifying such advantages and disadvantages usually not included in economical analyses of wind energy is often made by means of external cost analyses as we shall see at the end of this paper.

Atmospheric emissions

No direct atmospheric emissions are caused by the operation of wind turbines. The indirect emission from the energy used to produce, transport and decommission a wind turbine depends on the type of primary energy used.

Liabilities after decommissioning

Electricity from wind turbines has no liabilities related to decommissioning of obsolete plants. Today, most metal parts of wind turbines can be re-cycled. In a very near future other parts, such as electronics and blades, will be recycled almost 100p.c.

Energy balance

The direct environmental effects related with manufacturing of wind turbines is similar to those of other equipment production processes, and the indirect environmental effects of the energy used to produce a wind turbine depend on the type of primary energy used. Several early investigations have shown, that the energy invested in production, installation, operation & maintenance and decommissioning of a typical wind turbine has a "pay-back" time (energy balance) of less than a year of operation (World Energy Council, 1994).

New up-dated surveys have confirmed this (Krohn, 1996). Manufacturing a state-of-the-art 600 kW wind turbine takes 3.2 TJ taking into account everything from producing raw material to installing a ready machine, including 20 years of operation and maintenance and decommissioning. In suitable locations, the wind turbine will generate 1.1 to 1.3 million kWh per year in its projected 20-year useful life. The energy invested in a state-of-the-art 600 kW wind turbine is therefore repaid over 3-4 month.

Land use

Wind energy is diffuse and collecting energy from the wind requires turbines to be spread over a wide area. As a rule of thumb wind farms require 0.08 to 0.13 km^2/MW (8 - 13 MW/km^2). The area needed for 100,000 MW is less than 0.3% of the territory covered by the European Union. Onshore wind farms have the advantage of dual land use. 99% of the area occupied by a wind farm can be used for agriculture or remain as natural habitat. Furthermore, part of the installations can be made offshore. Consequently, limited area of land is not a physical constrain for wind power utilisation, as it could be for large scale utilisation of biomass in energy production.

Noise emissions

Acoustic emissions from wind turbines are composed of a mechanical and an aerodynamical component, both of which are a function of wind speed. Analysis shows that for most turbines with rotor diameters up to 20 m the mechanical component dominates, whereas for larger rotors the aerodynamical component is decisive.

The nuisance caused by turbine noise is one of the important limitations of siting wind turbines close to inhabited areas. The acceptable emission level strongly depends on local regulations. An example of strict regulation is the Dutch regulation for 'silent' areas, where a maximum emission level of 40 dB(A) near residences is allowed, at a wind speed of about 5-7 ms^{-1}. At this wind speed level the turbine noise is most distinctly audible. In Europe a typical distance between wind turbines and the nearest house is more than 150 or 200 meter.

Visual impact

Depending on the characteristics of the landscape modern wind turbines with a hub height of 40 - 60 meters and a blade length of 20 - 30 meters form a visual impact on the landscape. This visual impact, although very difficult to quantify, can be a planning restriction in most European countries.

Moving shadows

A more objective case of visual impact is the effect of moving "shadows" from the rotor blades. This is only a problem in situations where turbines are sited very close to workplaces or dwellings. The effect can easily be predicted and avoided through proper planning. A house 300 meter from a modern 600 kW machine with a rotordiameter of 40 meter will be exposed to moving shadows approx. 17-18 hours out of 8760 hours annually.

Erosion

On the typical flat on-shore sites installation of wind turbines has no erosional effects and the installation does not to any significant level affect vegetation or fauna. In most countries wind power developers are obliged to minimise any disturbance of vegetation under construction of wind farms (in combination with road works etc.) on sensitive sites such as mountainous sites and offshore.

Impact on birds

The impact of wind turbines on birds can be divided into:

- direct impact including risk of collision and effect on the breeding success
- indirect impact including effects caused by disturbance from the wind turbine (noise and visual disturbance). The disturbance effects of wind turbines fall into three categories:
    - disturbance to breeding birds
    - disturbance to staging and foraging birds
    - disturbing impact on migration/flying birds

Studies in Germany, the Netherlands, Denmark and the UK conclude, that wind turbines do not pose any substantial threat to birds (or bats or insects). Bird mortality due to wind turbines is only a small fraction of the background mortality (Still et al. 1994). A study has estimated an maximum level of birds collision with wind turbines of 6 - 7 birds/turbine/year (Clausager & Nøhr, 1995). In Denmark with approximately 4000 wind turbines this means that 25,000 to 30,000 birds annually die from collision with wind turbines. As comparison it can be mentioned that over one million birds are killed in the traffic in Denmark, and that the total number of staging and migrating birds in Denmark is 400 - 500 millions. Isolated examples have been reported of significant damages on specific species, such as the Spanish wind farm of Tarifa near the Strait of Gibraltar, which is a major bird migration route (Llamas, 1995). The problem was caused by very special circumstances, and it seems to have been solved without removing the turbines.

If not properly dealt with, wind farms sited on coastal sites can disturb breeding and resting birds. Typically, an effect has been recorded within 250-800 meter, with a highest sensitivity recorded for geese and waders. Including professional knowledge of birds and wind turbines in the planning process or wind farms can solve this problem. A European Best Practice for siting wind farms with respect to birds would be of great help for European wind farm developers in avoiding disturbance of birds.

Interference with electromagnetic communication systems

Wind turbines in some areas can reflect electromagnetic waves, which will be scattered and diffracted. This means that wind turbines may interfere with telecommunication links. An investigation made by the British company BBC concluded, that wind turbines' interference with electromagnetic communication systems is no significant problem.

The IEA has provided preparatory information on this subject, identifying the relevant wind turbine parameters (diameter, number and cross-section of blades, speed, etc.) and the relevant parameters of the potential vulnerable radio services (spatial positions of transmitter and receiver, carrier frequency, polarisation, etc.). Planning of wind farms, areas where wind turbines could interfere with telecommunication are normally avoided.

Personelle safety

Accidents with wind turbines involving human beings are extremely rare, and there is no recorded cases of persons hurt by parts of blades, parts of blades or ice loosened from a wind turbines. Insurance companies in USA, where most of the experience with large wind farms has been occurring, agree that the wind industry has a good safety profile compared to other energy producing industries. The International Electrical Committee (IEC) has issued an international official standard on wind turbine safety.

Social or external costs

External or social costs of wind power (or other energy producing technologies) are costs imposed on the society or the environment that are not accounted for by the producers and consumers of energy (Eyre, 1994). Several international surveys conclude that electricity from wind turbines has very low external costs. Several methods can be applied to determine the external cost of energy producing technologies and several ongoing research projects investigateexternal costs of different technologies. In the European study "ExternE" wind farms in the UK were analysed and the same method has been used in Spanish wind farms. The results can be seen from table 4. As can be seen, the total external costs of wind energy are of the order of 0.1 to 6.7 mECU/kWh.

In a Danish study the external costs of wind power are compared with those of N-gas, biomass and coal-burning plants (Meyer et al. 1994). As can be seen from the table external costs of coal based electricity are orders of magnitudes higher than for wind power.

The surveys conclude, that the most important impacts of wind farms are noise and visual intrusion. These issues must be dealt with when planing wind farms.

Site	Delabole, UK	Spain
Noise	1.1	0.0008
Visual amenity	N/Q[1)]	0 - 3.9
Global warming	1.15	0.1 - 0.65
Acidification	0.7	0.01 - 1.03
Accidents	0.09 - 0.35	0 - 1.135
Total	3.04 - 3.3	0.11 - 6.71

Table 2. External costs of wind energy (mECU/kWh). 1) Not quantifiable, but mentioned as the most important. Source: Eyre, 1994 and Llamas, 1995.

Electricity producing technology	External costs in mECU/kWh
Wind power	0.14 - 1.5
Biomass	0.5 - 8.8
N-gas	0.5 - 7.4
Coal	1.6 - 20.7

Table 3. External costs of different electricity producing technologies. Source: Meyer, et al.

BEGINNER'S GUIDE TO WIND ENERGY STUDIES

Key literature to the international history of wind power and wind turbines are the books by Putnam (1948), Golding (1955 and 1976) and Simmons (1974) and the two NASA reports by Vargo (1974) and Shephard (1990). Simmons book contains an overview of both the 20'th century history and the state-of-the-art of wind turbines in the mid-seventies with a chapter for each of 12 countries all over the world, but with emphasis on USA and Canada.

Another important source to the history of modern wind power is the "Proceedings of the United Nations Conference on New Sources of Energy". This conference was held in Rome in 1961, but the proceedings were published in 1964. These proceedings contain key sources of information of the Danish development in wind power in this century, (Juul, 1964; Arnfred, 1964).

Also wind engineering textbooks often contain an introduction with a historical overview (Johnson, 1985; Eggleston and Stoddard, 1978; Freris, 1990).

The above sources primarily take engineering and economical perspectives on wind power. The latest development in wind power (the post-oil-embargo history) is treated from a political-science/historical point of view by Karnøe (1991) and Heymann (1990).

I have referred to the UN conference in 1964, but proceedings from some other international conferences can be of interest to those who want more information. A UNESCO conference on wind and solar energy was held in New Delhi in October 1954, and a World Power Conference was held in Brazil in July 1954 (Golding, 1976). Since the

1970's a number of international conferences are held annually or biannually all over the world. In Europe two major conferences are held: The European Community Wind Energy Conference (EWEC) is held biannually-annually and sponsored by the Commission of the European Communities and the European Wind Energy Association (EWEA), and the Wind Energy Conversion conferences also held biannually-annually and sponsored by the British Wind Energy Association (BWEA). In America the American Society of Mechanical Engineers (ASME) Wind Energy Symposium are held annually sponsored by The Solar Energy Division of ASME, and the Wind Power conference is sponsored by the American Wind Energy Association (AWEA) and the U.S. Department of Energy (DOE)

Some scientific journals may be of interest, too. In America ASME is issuing a *Journal of Solar Energy Engineering* and DOE is issuing *Current Abstracts: Wind Energy Technology*. In Europe *Wind Engineering* is the official journal of the British Wind Energy Association & the European Wind Energy Association, and a *Wind Engineering Abstracts* is also available. Both are issued by Multi-Science Publishing Company Ltd., Brentwood, Essex, UK.

A number of journals and magazines cover the latest development within technical, political, industrial, and economical aspects of modern wind power. In English that is: *Wind Power Monthly News Magazine*, *WindStats Newsletter*, *Wind Energy Weekly*; in German: *Wind Energie Aktuell - Monatliche Fachzeitschrift für Windenergie*, *Wind-Kraft & Natürliche Energie Journal*; in Danish: Naturlig Energi, Vindstyrke Månedsmagasin.

Selected text books on wind energy and wind turbines

For engineers and persons who are technically interested, I have listed a number of textbooks below.

In English:

L. Freris (ed.)
Wind Energy Conversion Systems
Prentice Hall, Hempstead, England, 1990

David Spera (ed.)
Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering
ASME, New York, USA 1994

David M. Eggleston & Forrest S. Stoddard
Wind Turbine Engineering Design
Van Nostrand Reinhold, New York, USA, 1987

Godfrey Boyle
Renewable Energy. Power for a Sustainable Future
Oxford University Press, Oxford, UK, 1996

Paul Gipe
Wind Power for Home & Business
Chelsea Green Publishing Company, Vermont, USA, 1993

Paul Gipe
Wind Energy Comes of Age
John Wiley & Sons, New York, USA, 1995

Walker, John F & Nicholas Jenkins
Wind Energy Technology
UNESCO, John Wiley & Sons, Chishester, UK, 1997

In German:

Erich Hau
Windkraftanlagen. Grundlagen, Technik, Einsatz, Wirtschaftlichkeit.
Springer-Verlag, Berlin, 1988

Jens-Peter Molly
Windenergie: Theorie, Anwendung, Messung.
Verlag C. F. Müller, Karlsruhe, Germany, 1990

In French:

Dèsirè le Gourières
Energie Eolienne: Theorie, conception, et calcu practique des installations.
Editions Eyrolles, Paris, 1980

REFERENCES

Andersen, P. D. (1993)
Technological Innovation in the Danish Wind Turbine Industry. (In Danish)
Samfundslitteratur, Copenhagen.

Andersen, P. D.; P. H. Jensen; J. Beurskens (1995)
Environmental Consequences of Windpower
In: World Energy Council (1995).

Andersen, P. D.; P. H. Jensen; E. L. Petersen; J. Beurskens; G. Elliot; J. P. Molly
Wind Energy
In: EUREC Agency (1996)

Arnfred, J. T. (1964)
Developments and Potential Improvements in Wind Power Utilization.
In: United Nations, 1964

Clausager, I.; H. Nøhr (1996)
Impact of Wind Turbines on Birds. An overview of European and American Experiences
Paper Presented at the European Commissions Wind Energy Conference, May 1996, Göteborg, Sweden.

Durstewitz, M; M. Hoppe-Kilppner; W. Kleinkauf; N. Stump; R. Windheim (1996)
Technische und Ökonomische Aspekte der Windenergienutzung in Deutschland
In: Jahresauswertung 1995, Institut für Solare Energieversorgungstechnik, Kassel.

Eggleston, David M. and Forrest S. Stoddard (1987)
Wind Turbine Engineering Design.
Van Nostrand Reinhold Company, New York.

Elliott, D.A.
Public Reactions to Windfarms: The Dynamics of Opinion Formation
Energy & Environment, Vol.5, 1994, Issue 4.

Elliot, George (ed.) (1987)
Recommended Practices for Wind Turbine Testing. Part 8. Glossary of Terms, Issue 1.
National Engineering Laboratory, East Kilbride, Glasgow, UK

Energi&Miljødata (1996). Personal communication.

EUREC Agency (1996)
The Future for Renewable Energy: Prospects and Directions
James & James, London.

European Commission (1996)
Green Paper on Innovation
ECSC-EC-EAEC, Brussel/Luxembourg.

European Commission (1995)
For a European Union Energy Policy - Green Paper
ECSC-EC-EAEC, Brussel/Luxembourg.

European Commission (1993)
Growth, Competitiveness, Employment. The Challenges and Ways Forward into the 21st Century. - White Paper.
ECSC-EC-EAEC, Brussel/Luxembourg

EWEA (1991),
Time for Action - Wind Energy in Europe
European Wind Energy Association

Eyre, Nick (1994)
Externalities of Fuel Cycles "Externe" project. Wind Fuels. Working Document No. 7
European Commission, DG XII, 1994.

Freris, L. L. (ed.) (1990)
Wind Energy Conversion Systems.
Prentice Hall, New York.

Golding, E. W. (1976)
The Generation of Electricity by Wind Power. 2nd edition.
Halsted Press (Wiley), New York.
(First published in 1955. 1976 edition is with an additional chapter by R. I. Harris)

Heymann, Matthias (1990)
Why were the Danes Best? Wind Turbines in Denmark, West Germany and the USA 1945 - 1985.
Paper presented at the SHOT Annual Meeting 18.-21. Oct. 1990, Cleveland, USA.
Deutsches Museum, München

Holst, Helge (1923)
Book of Inventions, Vol 1 (in Danish)
Nordisk Forlag, Copenhagen

IAEA (1991)
Key Note Papers
Senior Expert Symposium on Electricity and The Environment, Helsinki, Finland, 13-17th May 1991, International Atomic Energy Agency, Vienna 1991.

International Energy Agency (1996),
IEA Wind Energy Annual Report 1995,
National Renewable Energy Laboratory, Colorado, USA

Johanneson T. B., Kelly, Reddy, Williams (eds) (1993)
Renewable Energy. Sources for Fuels and Electricity
Island Press, Washington D.C.

Johnson, Gary L. (1985)
Wind Energy Systems.

Prentice-Hall, Inc., Englewoods Cliffs.

Juul, J. (1964)
Design of Wind Power Plants in Denmark.
In: United Nations, 1964.

Karnøe, Peter (1991)
Dansk Vindmølleindustri - en overraskende international succes. (in Danish)
Samfundslitteratur, Copenhagen.

Krohn, S. (1995)
Danish Wind Turbines Energy Balance (In Danish).
In: Vindkraft Note, No. 3, December 1995
Danish Wind Turbine Manufacturers Association, Copenhagen.

Llamas, P. L. (1995)
The Environmental Cost of Wind Energy in Spain
Paper presented at EWEA Special Topic Conference '95, Helsinki, Finland.

Meyer, H., P.E. Morthorst, L. Schleisner, N.I Meyer, P.S. Nielsen and V. Nielsen (1994)
Determination of the environmental externalities associated with energy production (In Danish)
Risø-R-770(DA), Risø National Laboratory.

OECD/IEA, NEA (1993)
Projected Costs of Generating Electricity. Update 1992
OECD, Paris.

Putnam, P. C. (1948)
Power from the Wind.
Van Nostrand, New York

Pulczynski, Jörn (1991)
Interorganisationales Innovationsmanagement. (In German)
Wissenschaftsverlag Vauk Kiel KG.

Shepard, Dennis G. (1990)
Historical Development of the Windmill.
NASA Contractor Report 4337, (DOE/NASA 5266-2).

Simmons, Daniel M. (1975)
Wind Energy.
Noyes Data Corporation, New Jersey (ISBN 0-8155-0575-2)

Still, D., B. Little, S. G. Lawrence and H. Carver (1994)
The Birds of Blyth Harbour
Paper presented at the BWEA '94 Conference.

United Nations (1964)
Proceedings of the United Nations Conference on New Sources of Energy. Rome, 21-31 August 1961. VOLUME 7, Wind Power.
United Nations, New York 1964

Vargo, D. J. (1974)
Wind Energy Development in the 20'th Century.
NASA Technical Memorandum, NASA TM X-71634, September 1974.

Watson, R. T; M. C. Zinyowera; R. H. Moss (eds.) (1996)
Climate Change 1995. Impacts, Adaption and Mitigation of Climate Change: Scientific-Technical Analyses
Cambridge University Press.

World Energy Council (1995)
Local & Regional Energy-Related Environmental Issues
World Energy Council, London, UK, September 1995.

World Energy Council (1994)
New Renewable Energy Resources - A Guide to the Future.
Kogan Page, London. ISBN 0 7494 1263 1

World Energy Council (1993)
Energy for Tomorrow's World
Kogan Page, London, ISBN 0 7494 1117 1

Published in 1999

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Publications Review of Historical and Modern Utilization of Wind Power Per Dannemand Andersen, Ph.D. Content INTRODUCTION THE HISTORY OF WIND POWER. Wind Power in Denmark. Applications of wind power. Wind power utilization today wind power technology. Modern wind turbine technology. Concepts. Cost of wind energy. Types of ownership environmental aspects of wind power utilisation. Atmospheric emissions Liabilities after decommissioning Energy balance Land use Noise emissions Visual impact Moving shadows Erosion Impact on birds Interference with electromagnetic communication systems Personelle s