WIND ENERGY

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Introduction

The cost of electricity generated from wind turbines is now comparable to the cost of electricity produced by fossil-fuel-generators. It seems likely that wind power will become a substantial source of electrical power around the world and could therefore contribute to reduction in anthropogenic CO_2 emissions. At the end of 2001, the United States had an installed wind generating capacity of about 4,200 megawatts and the world's total was 24,000 megawatts [1]. The American Wind Energy Association estimates the world total wind energy installed capacity at the end of 2002 will be 30,000 megawatts [1]. By 2003, wind power will account for about 21% of Denmark's electricity production [2]. According to their "Plan 21," Denmark intends to get 50% of its electrical power from wind by 2030. As a point of reference, the electrical generating capacity of the US is about 9×10^5 MW ([3], p. 12).

Wind energy is one of the renewable means of electricity generation that is part of the worldwide discussion on the future of energy generation and use and consequent effects on the environment. We believe that there should be wider participation in this important debate, including more technically well-educated people such as members of the APS. There are many research problems that could be attacked by physicists, including, for example, materials for turbine vanes (limits wind turbine size), semiconductor materials and power electronics for electric power conditioning, and long-distance electrical transmission (superconducting transmission lines). In this report we discuss basic technical and economic aspects of wind energy and hope to provide a helpful guide to some important issues and literature relevant to this technology.

Wind [4, 5]

The sun warms the Earth's surface by variable amounts at different locations, thereby creating differential pressures which initiate air motions. Thus wind is a manifestation of solar energy. Heating is greatest at the equator, and, in the upper layers of the atmosphere, air flows away from the equator. In the northern hemisphere, the Coriolis effect continuously forces air to the right of its current motion (the opposite is true in the southern hemisphere). At about 30º latitude, the air moving northward from the equator in the upper atmosphere descends to lower levels and forms a zonal latitude region of high surface air pressure. There are other large-scale circulation structures between 30º and the poles. These high-altitude airflows above about 1-3 km are not affected by frictional forces induced by interactions at the Earth's surface.

"Surface" winds (below about 1-3 km) are very much affected by surface roughness and obstacles. Mountains, valleys and other topographic features can concentrate and increase wind velocities. At a seacoast during the day, air expands and rises over hotter land surfaces and flows out to sea in the upper atmosphere, and air at lower levels moves from the sea to the land,

producing a cool "sea breeze." At night, the flow reverses, and the prevailing shore winds near the surface blow from land to the sea.

The power available from moving air is proportional to the cube of the wind velocity. This can be seen simply as follows. If one considers a mass of moving air, its kinetic energy is proportional to the square of the velocity. The power is then proportional to how much air passes the wind turbine per unit time, i.e.,

$$P(v) = \frac{1}{2}\rho A v^3 \qquad [1]$$

where A is the airflow cross-section, ρ is the air density and v is the air velocity.

As the air passes through the plane of the turbine vanes, it slows down and therefore must spread out, as there is no significant compression.

The wind turbine cannot take all of energy from the moving air, since the air would then have to stop dead. It was shown in 1919 by Albert Betz that, for any wind turbine, the optimum energy extraction occurs when the wind speed behind the turbine is 1/3 the incident wind speed, in which case a theoretical maximum of 59% of the energy of the moving air can be extracted ([6], Chapter 4). Wind turbines using aerodynamically-designed rotor blades can achieve absolute efficiencies as high as 45-50% ([6], Chapter 5").

The distribution of wind speeds can often be approximated by a Weibull/Rayleigh distribution $f(v) \sim v \exp\left(-v^2\right)$ ([6], p 455ff). We choose normalization constants for this distribution so that $\int f(v)\, dv = 1$.

$$f(v, v0) = \frac{\pi}{2}\frac{v}{v0^2}\ \exp\left(-\frac{\pi}{4}\frac{v^2}{v0^2}\right) \qquad [2]$$

$v0$ is the average velocity, i.e. $\langle v \rangle = \int v\, f(v, v0)\, dv = v0$. It is interesting to note that the Rayleigh distribution is the distribution of the rms value of Gaussian random noise.

Wind "classes" are set at varying levels of wind power and corresponding speeds shown in Table 1. These are calculated from the Rayleigh distribution, that is, the "wind power density" (col. 2) is calculated as $\text{Pwr density} = \int P(v)\, f(v, v0)\, dv$. In general, wind power is economical for areas with wind class 4 or greater with a possibility of extending the useful range to class 3.

Table 1. Wind classes at 50 m height showing power density per unit area [7].

Wind Power Class	Wind Power Density (W/m^2)	Rayleigh Average Wind Speed (m/s)
1	0-200	0-5.6
2	200-300	5.6-6.4
3	300-400	6.4-7.0
4	400-500	7.0-7.5
5	500-600	7.5-8.0
6	600-800	8.0-8.8
7	800-2000	8.8-11.9

Wind Turbines [1]

The most common modern wind turbine design is a metal tower with a three-bladed rotor (see Fig. 1 below).

Fig. 1. NEG Micon 1.5 MW wind turbine, 68 m diameter rotor, tubular steel tower. Blades are made of fiberglass. The rotor blades can be turned to optimize power and the entire tower is rotated to face the wind. ([5], “Megawatt-Sized Wind Turbines”)

The rotor blades for large turbines are generally fiberglass/epoxy composites with some admixture of carbon fiber. The latter is expensive but does offer strength advantages, and may be used increasingly in future designs [6]. The height of the tower can vary from about 1.5X to 3X the rotor radius. It is important to get the bottom of the blades well clear of the ground (or water surface, if the wind turbines are installed offshore) to avoid wind shear, that is, a differential airflow between the ground and upper parts of the rotor. Making the tower higher obviously adds cost and exacerbates potential problems of strength of the tower. Commonly, the tower direction

is actively controlled (rotated) so that the rotor faces into the wind. The design with rotor downwind from the tower has the disadvantage that the blades are shielded from the wind by the tower when they are pointed downward, and this creates additional strain on the rotor. The rotor design and operation is strongly based on experience with propeller-driven aircraft.

The nacelle (enclosure directly attached to the rotor) contains a gearbox and one or more generators. For large wind turbines, the rotor rotates about 20 to 40 rpm. The gearbox then gets a high-speed shaft rotating at about 1500 rpm. The high-speed shaft is then connected to an electrical generator [6, 8].

There are generally two ways to generate electrical power. One approach controls the rotational speed of the wind turbine in order to synchronize the electrical output with the power grid. The second allows the wind turbine speed to vary and produces ac electrical power at changing frequency. This power is then rectified to DC, "inverted" back to AC (synchronized to the grid) using thyristors or large transistors to a few hundred volts, and then raised again to 10kV to 30kV by transformers for transmission. The first method is simpler but has the disadvantage that it does not allow the wind turbine to be operated at its maximum efficiency at every wind speed. The second approach allows the turbine to operate most efficiently at the cost of expensive electronics [6, 8].

Wind turbine parts are designed for 20-30-year life, including storms [6]. That means approximately 120,000 to 180,000 hours of operation (assuming a 66% duty cycle). Cars last about 5,000 hours.

Wind turbines and wind turbine farms are closely monitored and computer controlled. Hundreds of parameters may be recorded, including wind speed and direction, voltage and current output, wind turbine direction, temperatures in various parts of the wind turbine system and so on. The tower must be automatically turned to keep the turbine facing into the wind, and the blade angles must be set to maximize the power extracted from the wind. Depending on the details of electrical generation, the wind turbine and electrical system must be monitored and controlled in order to smoothly transfer power to the grid [5, 6, 8].

Making wind turbines larger is desirable economically, and wind turbine sizes are slowly increasing. The limitations are, among other things, strength and durability of materials for the rotors and towers.

Table 2 shows the rotor diameter of wind turbines as a function of their power ratings.

Table 2. Rotor design diameters for wind turbines of varying power ratings. ([5], "Size of Wind Turbines.")

Power Rating (kW)	Rotor Diameter (m)
300	27-33
500	33-40
600	40-44
750	44-48
1000	48-54
1500	54-64
2000	64-72
2500	72-80

Power Curve

As indicated above, the power available from a moving air mass is proportional to the cube of the air velocity. The exact details of power output depend on the design and operation of the blades, generators etc.

Figure 2 shows a power curve for a 600 kW wind turbine. ([5], "The Power Curve of a Wind Turbine"). At a wind speed of about 15 m/s, the blades are adjusted to limit the power to about 600 kW. If the wind reaches 25 m/s, the turbine is shut down. (1 m/s = 2.24 mi/hr.)

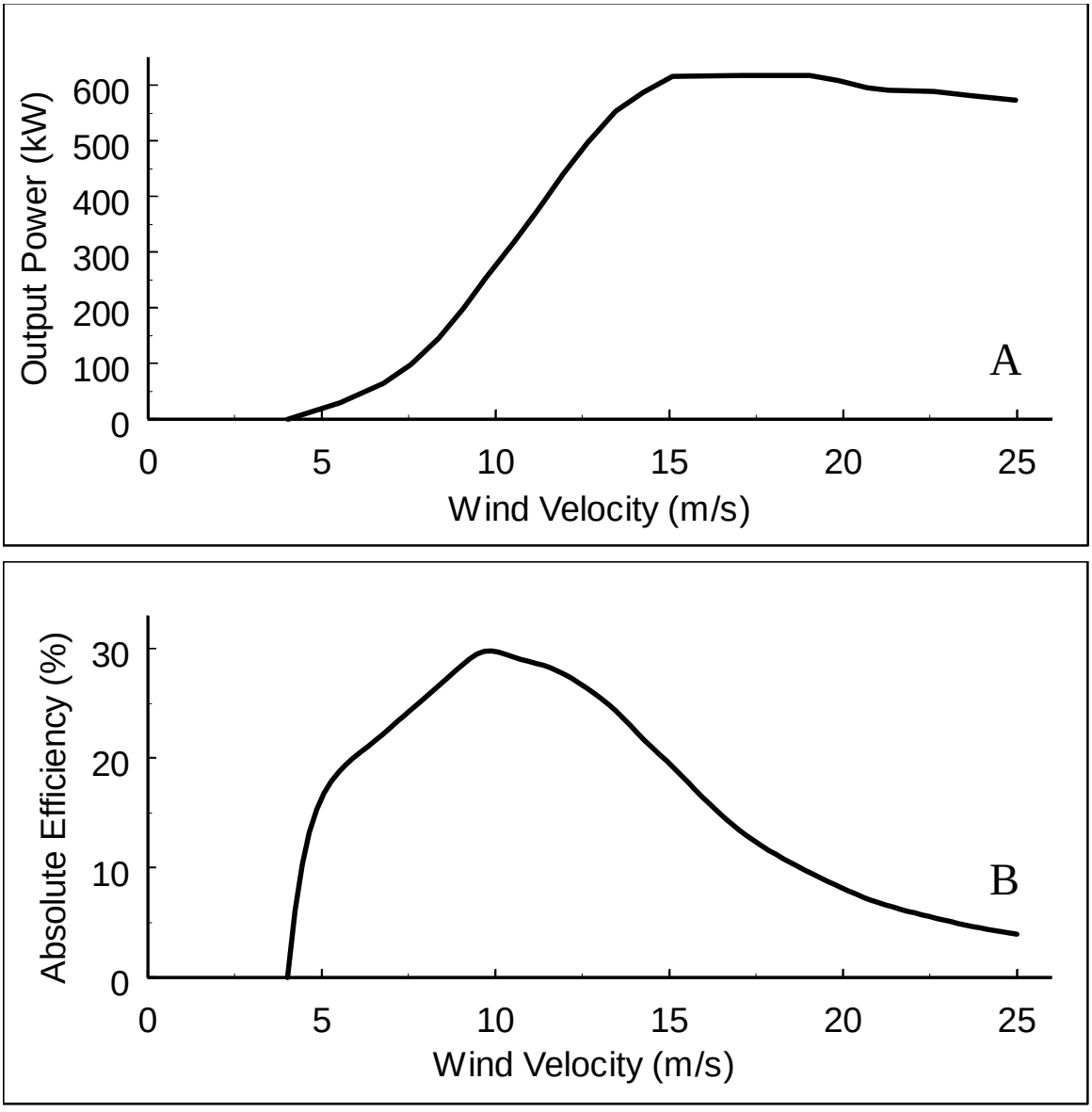


Figure 2. A) Power output for a 600 kW wind turbine. (Data digitized from [5], "The Power Curve of a Wind Turbine") B) Absolute efficiency of 600 kW wind turbine: power output (graph A) divided by total power in moving air mass.

We can find the net efficiency for power production by multiplying the Rayleigh wind distribution (Eq. 2) by the turbine power curve (Fig. 2A) and integrating. We then get the

relative efficiency curve shown in Fig. 3, which is the fraction of rated power for the average wind speed on the x-axis.

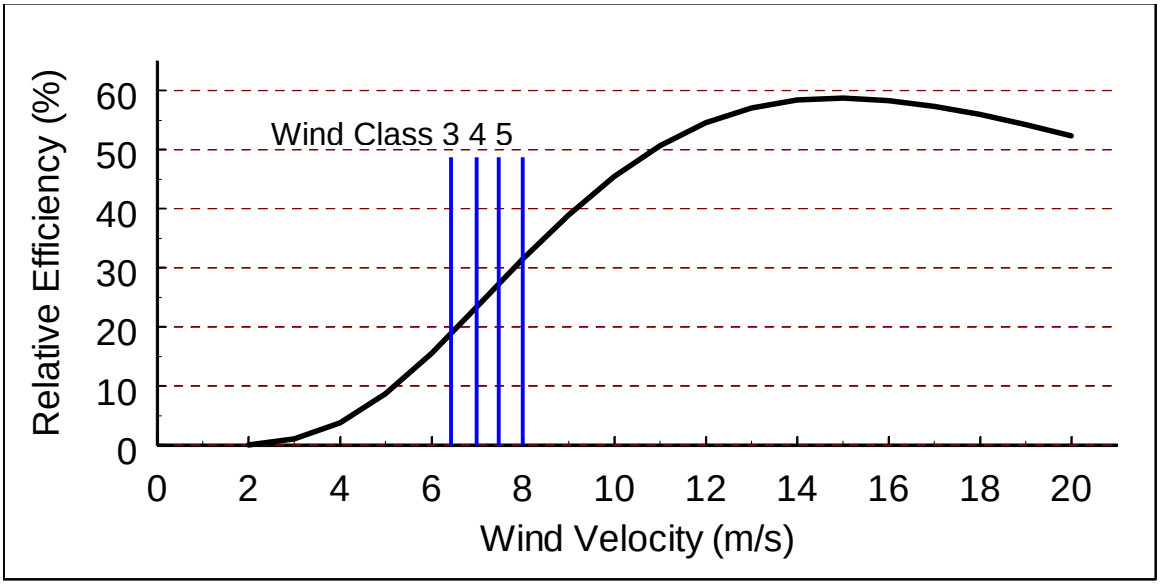


Figure 3. % rated power of 600 kW wind turbine for wind strength classes 3, 4 and 5 for wind turbine curve shown in Figure 2A (See Table 1). The horizontal axis is the *average* wind velocity at a given site assuming a Rayleigh distribution of wind velocity values.

It can be seen from the graph that the relative efficiency of this wind turbine is about 20% in class 3, 25% for class 4 and about 30% for class 5. Some turbines operate at up to 35% relative efficiency. ([5], "The Power Coefficient"; [9], Fact Sheet 14, "Efficiency and Performance.")

Wind turbines are usually specified at their maximum output. As indicated above, wind turbines generally operate at about 20-35% of their rated capacity, whereas fossil fuel electricity generators are designed to operate at full capacity and often do so. This is significant in understanding potential electrical power as a function of installed wind capacity and in considering the economics of wind power.

Issues and Concerns

Visual Impact of Wind Turbines

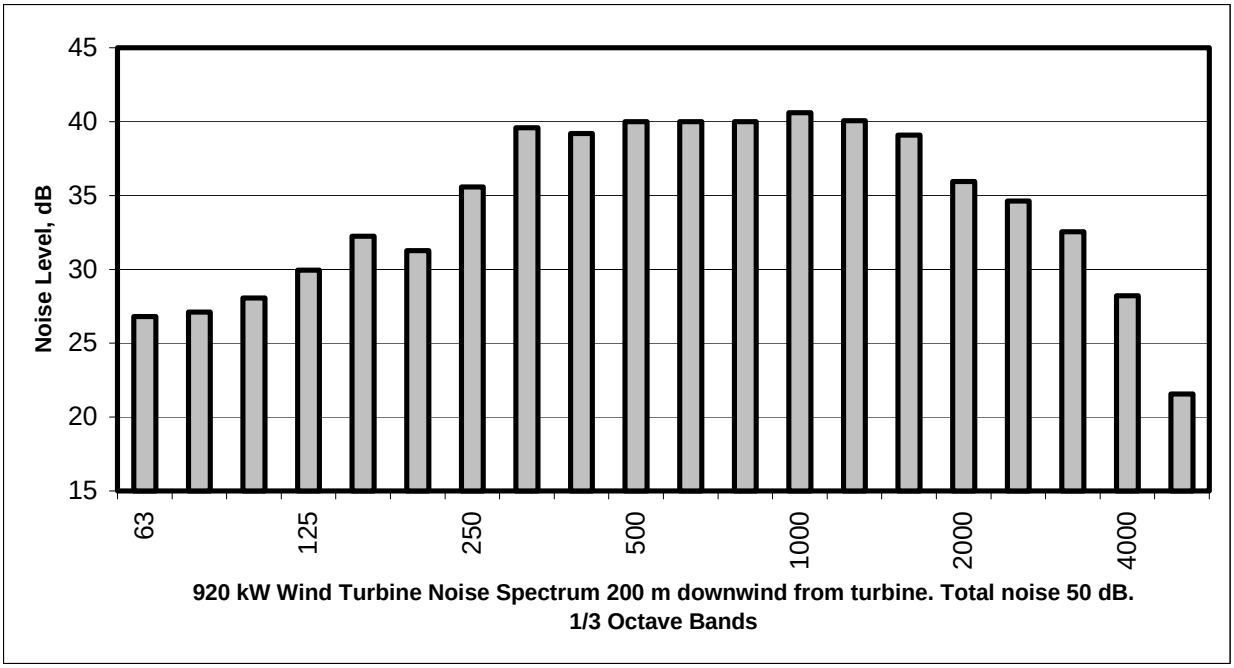
Wind turbines are tall (as much as 100-150 m high) manmade structures, which some people believe spoil the landscape, and therefore resist their establishment. There are often strong winds near seacoasts or in mountains, and wind turbines in these settings can be controversial [10, 11].

Noise

There are two sources of noise from wind turbines: mechanical noise, from the gearbox; and aerodynamic noise, from the rotating rotor. ([6], Ch 17; [8]; [12]; [5]: Designing for Low Mechanical Noise from Wind Turbines; Designing for Low Aerodynamic Noise from Wind Turbines; Sound from Wind Turbines.) Present-day gearboxes have been carefully designed and muffled to minimize noise, and modern, large wind turbines actually have less noise than smaller, older ones. This is because the rotors on large turbines go slower than those on small

turbines, and the amount of noise is proportional to the 5^{th} power of the angular velocity ([8], pg 84; [5], "Designing for Low Aerodynamic Noise from Wind Turbines).

The amount of noise from modern turbines is low. Figure 4 below shows the spectrum of a wind turbine operating at 920 kW ([6], p 60; [13]). If we apply scaling (from ref [6], pg 541), then the sound level will increase to 60 dB at a distance of about 66 m. 60 dB is about the noise level of a normal working office.



.Figure 5. Noise spectrum from WKA-60 turbine on Heligoland; [13])

Reference [5] says that for a ~1.5-2 MW generator, the noise level directly underneath is 55 dB. About 100 m away it is about 50 dB.) ([5], Sound from Wind Turbines: Noise is a Minor Problem Today.") If necessary, rotor speeds may be purposely limited to reduce noise [8]. In some circumstances, the background wind noise can be enough to mask the turbine noise [8].

Hazards to Birds [14]

There has been a significant problem with bird kills, particularly raptors, in Altamont Pass in California. In general, it would appear that bird collisions with wind turbines are a site-specific problem. Some possible solutions include: don't place wind turbines in places frequented by large numbers of birds (migration, food supply); try to make turbines and turbine blades more visible so birds will avoid them; reduce perching opportunities, for example, changing turbine towers from "latticework" towers to steel tubular towers.

Turbine robustness and reliability

Wind turbine rotor blades are subject to cyclic loading every revolution, which can cause material fatigue. The blades can also fail under extreme weather conditions. The composite rotor blades are a critical part of the wind turbine system that limits, for example, the overall size and consequent cost-effectiveness of wind energy [6, 8, 15].

Wind Power Now: The World

Table 3 shows the world market at this time. Germany has the greatest total capacity, while Denmark has the greatest fraction (20%) of its electricity generated by wind ([5], "Wind Energy News from Denmark"). Denmark plans to install 5500 MW capacity by 2030, which will then generate 50% of their electricity. Italy has a goal of 2500 MW by 2008-2012, Netherlands 2000 MW by 2007, Spain 10,000 MW by 2010. ([9], Fact Sheet 9, "The International Market")

Germany has over 11,000 wind turbines. Its installed base represents 3.5% of its electric power generation and it is planning to install up to 5000 turbines off its north coast. Some would be located up to 45 km off the coast [16].

Table 3. Installed Wind Energy (January 2002). The bigger number from the two references was used to compile this table. ([9], Fact Sheet 9, "The International Market"; [17].)

Country	MW	Country	MW	Country	MW
Germany	8754	Greece	273	Costa Rica	51
United States	4240	Japan	250	Ukraine	40
Spain	3337	Canada	200	Finland	39
Denmark	2417	Ireland	132	New Zealand	37
India	1426	Portugal	127	Belgium	31
Italy	697	Egypt	125	Brazil	20
Netherlands	493	Austria	94	Turkey	20
United Kingdom	474	France	87	Norway	17
China	361	Australia	74	Rest of world	118
Sweden	290	Morocco	54	**Total**	**24278**

Wind Power Now: The United States

United States

As shown in the table above, the United States presently has about 4240 MW of electrical wind energy capacity. In comparison, the electrical generating capacity of the US is about 9×10^5 MW ([3], p. 12). A list of wind energy projects throughout the country can be found at reference [18]. There are a various economic incentives that encourage wind power, including the Production Tax Credit (PTC, extended to the end of 2003) which provides a 1.5 ¢/kWh tax credit for wind-generated electricity [19].

At the present time the comprehensive energy bill is being negotiated between House and Senate versions. Both contain an extension of the PTC through 2006 [20].

Renewable Portfolio Standards (RPS) are one means that the government can use to increase the use of renewable energy sources. While included in the massive Energy Policy bill of the 107th Congress that died in conference (there was a 10% RPS in the Senate bill but not in the House bill [20]), RPS is more common at the state level where it has been instituted in a

variety of forms in many states. At the state level, RPS typically requires electricity providers that sell power to the state's residents to obtain a specified amount of electricity from renewable energy. The could start at a low level and then increment with time. For example, one might specify a target of 2% by 2004 and then increase to 10% by 2012. RPS usually also specifies that the renewable energy source must be a new source, which might be defined as having been built since 1998 to avoid power companies using older non-fossil-fuel sources such as hydroelectric dams.

Eight states now have RPS: Arizona, California, Connecticut, Maine, Massachusetts, Nevada, New Jersey and Texas [21, 22]. California's RPS, signed on September 12, 2002, requires 20% renewables electricity generation by 2017 [22]. Texas requires 1280 MW for renewables by 2003, 1730 MW by 2005 up to 2880 by January, 2009. This would then be 3% of their electrical supply [22].

California ([18], California)

California has the largest installed wind power base with 1671 MW and 660 MW planned as of January, 2002. Some major wind resource areas have a large wind energy capacity because of an accumulation of many small installations. For example: Altamont Pass, 548 MW; San Gorgonio Pass, 421 MW; Tehachapi Pass, 620 MW. According to reference [18], California could use wind to generate an average 6770 MW of electricity with annual energy use 59 B kWh. This puts California 17th in wind energy potential among US states. The electricity in use in California on October 2, 2002 was about 40,000 MW [23].

Texas ([18], Texas)

Texas has 1096 MW installed with plans for further 220 MW. The Wind Energy Potential is 136,000 MW, putting them in 2nd place among US states for potential wind power. Since 1999 there have been several large projects, including: 214 x 1300 kW (278.2 MW); 242 x 660 kW turbines (159.7 MW); 100 x 1500 kW (150 MW); 125 x 660 kW (82.5 MW); 107 x 1500 kW (160.5 MW); and 80 x 1000 kW (80 MW). These projects add up to 910 MW (out of 1096 MW total).

Economics

Wind turbines do not have fuel costs. However, their initial capital cost ($/kW produced) is higher than that for fossil fuel plants, which do have fuel costs. Therefore reducing the capital cost and increasing the efficiency of wind turbines is critical. That has been happening, as the raw equipment costs for a 1.5 MW wind turbine is now about $1 million (i.e. $750/rated kW or $3000/kW at 25% capacity factor [24].

Including balance of plant, the "total overnight cost" (initial capital cost) of conventional gas turbines is about $409/kW. These have a thermal efficiency of about 25-30%. High-temperature gas turbines cost about $460/kW with a thermal efficiency of 36%. Combined-cycle gas generation (high-temperature gas plus steam turbines) can have efficiencies approaching 60% with initial capital cost $608/kW. On this scale, wind power costs are said to be $1003/kW rated [25, 26], ([27], Table 40). Given that the capacity factor of wind power is about 25-30%, the real capital costs are 3-4 times that high. The net costs of different technologies ultimately depend on a complicated mixture of capital, O&M (operating and maintenance) and fuel costs [27, 28].

It is clearly desirable to run wind power at the maximum because of zero fuel costs in order to pay down the wind power capital cost. Because of relatively high capital cost, the high temperature gas generator and combined cycle generation are also best used when run at full load [28].

The exact costs of wind energy can further depend on other factors, such as location (land or sea), wind speed, distance to power lines, etc. It appears that wind-generated electricity costs are comparable to, if slightly higher than, fossil fuel generation costs. The picture is further complicated by the existence of subsidies, tax breaks and requirements for renewables-generated electricity such as RPS. Wind energy has many attractive features so that many governmental entities in the US and abroad are willing to pay the extra price, and wind-generated electricity is being installed in quantity in many places around the world. So cost, at this stage, is not a major obstacle. This high level of activity provides an opportunity for wind energy technology to improve and costs to decrease, which could make wind energy more competitive.

For one example of economic analysis of wind energy, reference [29] quotes a Lawrence Berkeley National Laboratory study [30] which concludes that a 50 MW wind farm would produce electricity at about 5¢ per kWh compared to 3.7¢ per kWh for gas-produced electricity. Further information about economics can be found in [6] and [31].

Commercial Activity

Wind turbine manufacturing is spread around the world, including Europe, the United States, India and China. Table 4 shows the ten largest manufacturers. About 45% of total capacity is made by Danish companies.

Table 4. Leading wind turbine manufacturers ([32], data originally from BTM Consult ApS).

	2001 MW Sold	2001 Market Share	2001 Total Installed MW	2001 Total installed share
Vestas (Denmark)	1648	24.1%	4983	20.0%
Enercon (Germany)	1036	15.2%	3206	12.9%
NEG Micon (Denmark)	874	12.8%	4510	18.1%
Enron/GE (US)*	865	12.7%	2288	9.2%
Gamesa (Spain)	648	9.5%	2125	8.5%
Bonus (Denmark)	593	8.7%	2306	9.3%
Nordex (Germany)	461	6.7%	1473	5.9%
MADE (Spain)	191	2.8%	783	3.1%
Mitsubishi (Japan)	178	2.6%	558	2.2%
REpower (Germany)	133	1.9%	379	1.5%
Others	448	6.6%	3482	14.0%
Total	7075		26,092	

* Note—GE purchased Enron Wind Power in May 2002.

The Future

Wind electricity generation is a healthy and growing international industry. The Danish consulting company BTM estimates that worldwide business will grow 16% over the next five years with sales volume estimated at almost $38 billion [33]. Denmark, Germany, Spain, and other European countries have ambitious plans for wind power expansion.

The United States wind energy capacity grew faster than that of the world market in 2001 and will continue to increase. The present wind power electricity production is about 0.5% of the US total, but has been growing at 30% per year for the past 5 years [34]. A single gas generating plant can produce from 200-500 MW of power, which is equivalent to 800-1500 MW of wind energy assuming a capacity factor of 25%. In order to produce such sizable amounts of electricity, then, it will be necessary to create installations each with hundreds of wind turbines of 1 MW and higher. As mentioned above, there are some examples of these, and it will take time to solve all the engineering problems associated with such large sites.

It is interesting to consider the role of wind power in the very long run and what fraction of world and US power it is likely to provide. Reference [34] mentions that the European Union predicts that wind power could supply 12% of the world's energy by 2020.

In principle, there is enough wind energy in the Great Plains states to provide 150% of US electricity [35]. Given the fluctuations of wind, 100% would not be practical. Denmark is aiming for 50% by 2030 so it will be interesting to see if that is a good choice. Creating a large electrical resource in the Great Plains states would pose the problem of transmission to distant population centers. Perhaps this is an opportunity for HTS superconducting transmission lines [36]. Alternatively, some of the copious electrical power produced in remote locations could be used to produce hydrogen for the "hydrogen economy."

There are many aspects of science and technology that must be explored in order to optimize the potential of wind energy. These include, but are not limited to, research on: better materials for rotor blades [37]; aerodynamics of rotor blades; improved power semiconductors for power conditioning; superconducting power transmission lines [36]. Reference [38] has a list of wind energy employer links for the USA.

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