Wind Energy for Electric Power

A REPP Issue Brief

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FORWARD

This paper presents a general background on utility-scale wind power, providing the interested reader with a basis for understanding wind power in general, as well as providing a solid foundation for further understanding of the technical, economic, and policy dimensions of wind power development world wide. The concepts in this paper are illustrated with economic data and current policy from the U.S. wind sector. The paper provides extensive references and links to well-established bodies of knowledge on wind power in written form and on the Web, enabling the reader to become aware of and conversant in the latest developments in wind power for clean energy generation.

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INTRODUCTION

Overview

Over 15,000 billion kWh of electricity are generated annually worldwide. Of this, about 65% is produced by burning fossil fuels and the remainder is obtained from other sources, including nuclear, hydropower, geothermal, biomass, solar and wind energy.[1] Only about 0.3% of this power is produced by converting the kinetic energy in the wind into electrical energy.[2] However, the use of wind for electricity generation has been expanding rapidly in recent years, due largely to technological improvements, industry maturation and an increasing concern with the emissions associated with burning fossil fuels. There is still more room to grow, as only a small portion of the useable wind resource is being tapped. Government and electrical industry regulations, as well as government incentives, play a large role in determining how quickly wind power is adopted. Effective policies will help level the playing field and ensure that wind can compete fairly with other fuel sources in the electricity market.

This paper focuses on utility-scale electricity generation from wind and provides an overview of the history, technologies, economics, environmental impacts, regulations and policies related to this use of wind power. References to other sources of information are provided throughout and in a separate section at the end.

Benefits of Wind Power

Wind power has many benefits that make it an attractive source of power for both utility-scale and small, distributed power generation applications. The beneficial characteristics of wind power include:

- *Clean and inexhaustible fuel*—Wind power produces no emissions and is not depleted over time. A single one megawatt (1 MW) wind turbine running for one year can displace over 1,500 tons of carbon dioxide, 6.5 tons of sulfur dioxide, 3.2 tons of nitrogen oxides, and 60 pounds of mercury (based on the U.S. average utility generation fuel mix).[3]
- *Local economic development*—Wind plants can provide a steady flow of income to landowners who lease their land for wind development, while increasing property tax revenues for local communities.
- *Modular and scalable technology*—Wind applications can take many forms, including large wind farms, distributed generation, and single end-use systems. Utilities can use wind resources strategically to help reduce load forecasting risks and stranded costs.
- *Energy price stability*—By further diversifying the energy mix, wind energy reduces dependence on conventional fuels that are subject to price and supply volatility.
- *Reduced reliance on imported fuels*—Wind energy expenditures are not used to obtain fuels from abroad, keeping funds closer to home, and lessening dependence on foreign governments that supply these fuels.

RESOURCES & TECHNOLOGY

This section explains where wind comes from and how it is harnessed to produce electricity. Because wind power technology has been treated extensively elsewhere, this paper does not go into great technical detail. For detailed technical information see, for example, the web sites of the Danish Wind Industry Association (www.windpower.org) and the U.S. Department of Energy's National Wind Technology Center (www.nrel.gov/wind), as well as the Wind Energy Technical Information page of the American Wind Energy Association's web site (www.awea.org/faq).

Source of Wind Energy

Wind energy, like most terrestrial energy sources, comes from solar energy. Solar radiation emitted by the sun travels through space and strikes the Earth, causing regions of unequal heating over land masses and oceans. This unequal heating produces regions of high and low pressure, creating pressure gradients between these regions. The second law of thermodynamics requires that these gradients be minimized--nature seeks the lowest energy state in order to maximize entropy. This is accomplished by the movement of air from regions of high pressure to regions of low pressure, what we know as wind. Large-scale winds are caused by the fact that the earth's surface is heated to a greater degree at the equator than at the poles.

Prevailing winds combine with local factors, such as the presence of hills, mountains, trees, buildings and bodies of water, to determine the particular characteristics of the wind in a specific location. Because air has mass, moving air in the form of wind carries with it kinetic energy. A wind turbine converts this kinetic energy into electricity. The energy content of a particular volume of wind is proportional to the square of its velocity. Thus, a doubling of the speed with which this volume of air passes through a wind turbine will result in roughly a fourfold increase in power that can be extracted from this air. In addition, this doubling of wind speed will allow twice the volume of air to pass through the turbine in a given amount of time, resulting in an eightfold increase in power generated. This means that only a slight increase in wind velocity can yield significant gains in power production.

$\mathbf{E_k = \frac{1}{2} \cdot m \cdot \mathit{v}^2}$ The amount of kinetic energy in an air mass (E_k) is equal to half the product of its mass (m) and the square of its velocity (v).	$\mathbf{P \sim \mathit{v}^3}$ The amount of power (P) exerted by the wind is proportional to the cube of its velocity (v).

Wind Turbines and Wind Parks

A wind turbine is a mechanical assembly that converts the energy of wind into electricity. The three key elements of any wind turbine are the rotor, the nacelle—which contains the gearbox, the generator and control and monitoring equipment (see Figure 1)—and the tower. Modern utility-scale wind turbines typically are equipped with three-bladed rotors ranging from 42 to 80 meters (138 to 262 feet) in diameter, contain generators with rated capacity of between 600 kW and 2 MW, and are mounted on towers that are between 40

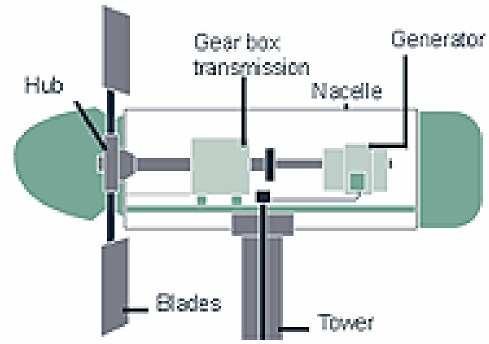


Figure 1. Above: Nacelle Components. Source: Sustainable Energy Development Authority, NSW, Australia (http://www.seda.nsw.gov.au/ren_wind_body.asp)

Figure 2. Left: A 600 kW Vestas American Wind Technology, Inc. turbine at Medicine Bow, Wyoming. Source: DOE/NREL (http://www.nrel.gov/data/pix)

and 100 meters (131 and 328 feet) tall (see Figure 2).[4] A utility-scale wind installation, called a wind farm or wind park, consists of a collection of these turbines.

Siting Considerations

Accurate estimates of wind speed are critical to assessing the wind power potential at any location. Wind resources are characterized by wind power density classes, which range from Class 1 (the lowest) to Class 7 (the highest). The U.S. Department of Energy has developed a map that identifies areas with good wind potential in the U.S. (see http://rredc.nrel.gov/wind/pubs/atlas/). These areas (class 3 and above) are found along the East Coast, the Appalachian Mountain chain, the Great Plains, the Pacific Northwest and in some other locations. In total, they cover more than 1 million square kilometers, or about 14% of the land area of the 48 contiguous states. However, estimates suggest that wind power generation on only 43,000 square kilometers of land—with less than 5% of this actually occupied by turbines, electrical equipment and access roads—could supply about 560 billion kWh of electricity annually, equivalent to about 15% of total U.S. demand.[5]

The roughness of the surface across which the wind blows before arriving at a turbine determines the amount of turbulence that a turbine will experience. Turbulent winds put greater stresses on the rotor and tower, reducing the turbine's lifespan as a result. Thus, the vast majority of wind farms are in rural locations, away from wind-disrupting buildings, trees and other obstacles.

While the technical characteristics of the wind in a specific location are very important, many other factors also contribute to siting decisions. A location far removed from the power transmission grid might be uneconomic, as new transmission lines will be required to connect the wind farm to the grid. Existing transmission infrastructure may need to be upgraded to handle the additional supply. Soil conditions and the terrain must be suitable for the construction of the towers' foundations. Finally, the choice of a location may be limited by land use regulations and the ability to obtain the required permits from local, regional and national authorities.

Tower Height

Tower height affects the amount of power that can be extracted by a given wind turbine, as well as the stresses on the rotor and nacelle. One kilometer above the ground, wind speeds are not influenced by the terrain below. The wind moves more slowly at lower heights, with the greatest reduction in wind speed found very close to the ground. This phenomenon, known as wind shear, is the key factor when deciding on tower height, as higher rotors are exposed to faster winds. In addition, the difference in wind speeds between the top and bottom of the rotor decreases with height, causing less wear on the turbine.

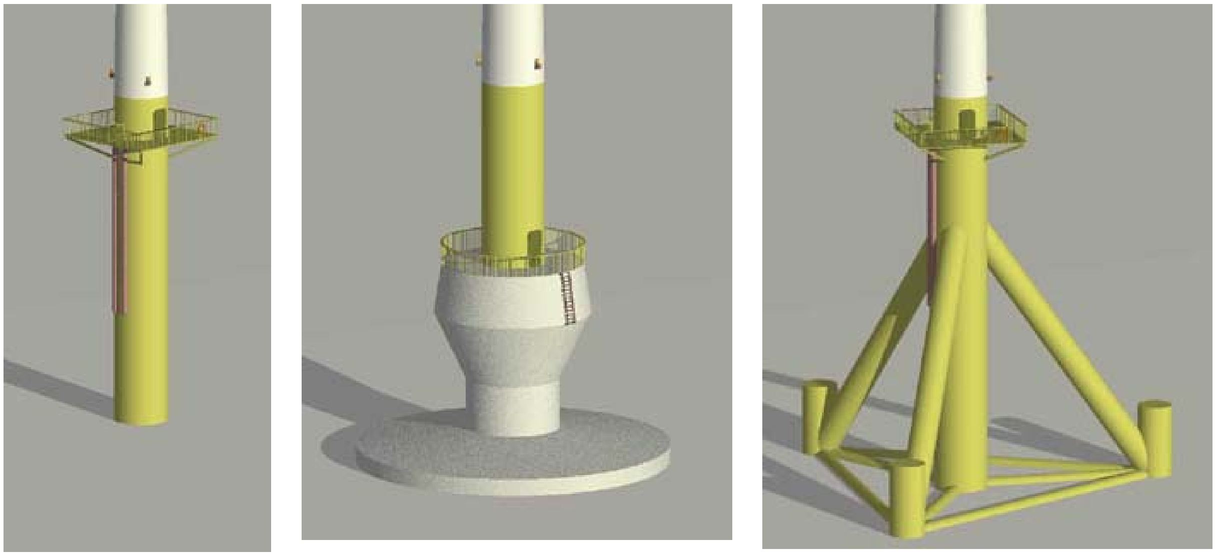
Offshore Wind Resources

Average wind speeds over water are typically 20% higher than nearby locations on land. Thus, due to the cubic relationship between velocity and power, an offshore turbine can expect to capture 50% more wind energy than a similar onshore turbine. In addition, because of the lower wind shear at a given height above water compared to that same height above land, offshore turbines can be built with shorter towers and can last longer (see discussion of wind shear above).[6]

Several foundation types are currently in use (see Figure 3). The mono pile foundation—used in more than half of existing offshore wind farms[7]—consists of a single steel pile driven or drilled into the seabed. The gravitation foundation consists of a steel box sitting on the seabed that supports a cylindrical tube. The tripod foundation consists of three smaller piles connected by a frame to a central pile.[8] Regardless of foundation type, the wind turbine's platform and tower sit atop the foundation, above the water.

Due to technical and economic limitations, offshore wind farms are currently limited to relatively shallow waters. In the future, wind turbines could be mounted on floating platforms, tethered to the sea floor. These turbines could be situated in deeper waters where they would be invisible from land and could take advantage of even stronger open-ocean winds. Instead of feeding electricity into the grid, they could be used to produce hydrogen that would then be shipped or piped to shore. Preliminary feasibility studies suggest that facilities of this type could be built; however, further research is needed before such a wind farm can become a reality.[9]

Figure 3. Foundation Types for Offshore Wind: Monopile, Gravitation and Tripod



Source: Offshore Wind Energy (http://www.offshorewindenergy.org)

HISTORY

First Steps

Harnessing the wind for large-scale electric power generation is a relatively recent development. Wind had been used for hundreds of years to power sailing vessels and to drive windmills, but it wasn't until the late 19th century that the first wind turbine for electricity generation came into use. This windmill was built by Charles Brush (inventor of several technologies key to the then nascent electrical industry), stood 17 meters (50 feet) tall and had 144 rotor blades, all made of cedar wood. Soon thereafter Poul la Cour, a Dane, discovered that fast rotating wind turbines with fewer rotor blades generated electricity more efficiently than slow moving wind turbines with many rotor blades.[10]

20th Century Advances

This opened the door to a number of wind turbine advances during the 20th century. These included the introduction of AC generators, the standardization of the upwind model (in which the rotor is upwind of the nacelle), electromechanical yawing to ensure that the rotor always faces directly into the wind, and stall controls to keep the rotor from turning too fast in very strong winds.[11] Modern wind turbines make use of very few but very large blades to capture winds energy. Because these are large machines, they rotate relatively slowly, but generate large amounts of power while doing so.

The oil crisis of 1973 boosted interest in large wind turbines and sparked several government-sponsored research programs in Germany, Sweden, Canada, the U.K. and the U.S. Because of these efforts, the cost of wind power on a per-kWh basis was cut in half in less than a decade. Today's wind turbines generate power more cost-effectively than ever before, with the busbar cost dropping from 38 cents per kWh in the early 1980's to between two and six cents today, depending on location.[12] Wind power approaches competitiveness with conventional generation at this price point.

Wind Power Today

Wind power is the world's fastest growing source of electricity. Generating capacity grew at an average annual rate of 25% between 1990 and 2000, exceeding less than 2% annual growth in each of nuclear, oil and natural gas, and an average annual decline of 1% in coal consumption over this period.[13] As of the end of 2002 total global wind generating capacity exceeds 31,000 MW, and provides about 65 billion kWh of electricity annually.[14] This is enough to meet the needs of over 6 million average American homes.[15] Generating capacity is mainly concentrated in just five countries; Germany (36%), the U.S. (18%), Spain (14%), Denmark (10%) and India (6%) together account for 84% of the total (see Figure 4).[16]

As of the end of 2002, generating capacity in the U.S. was highly concentrated in just two states, California and Texas, which together accounted for about two thirds of the national total of 4,660 MW (see Figure 5).[17]

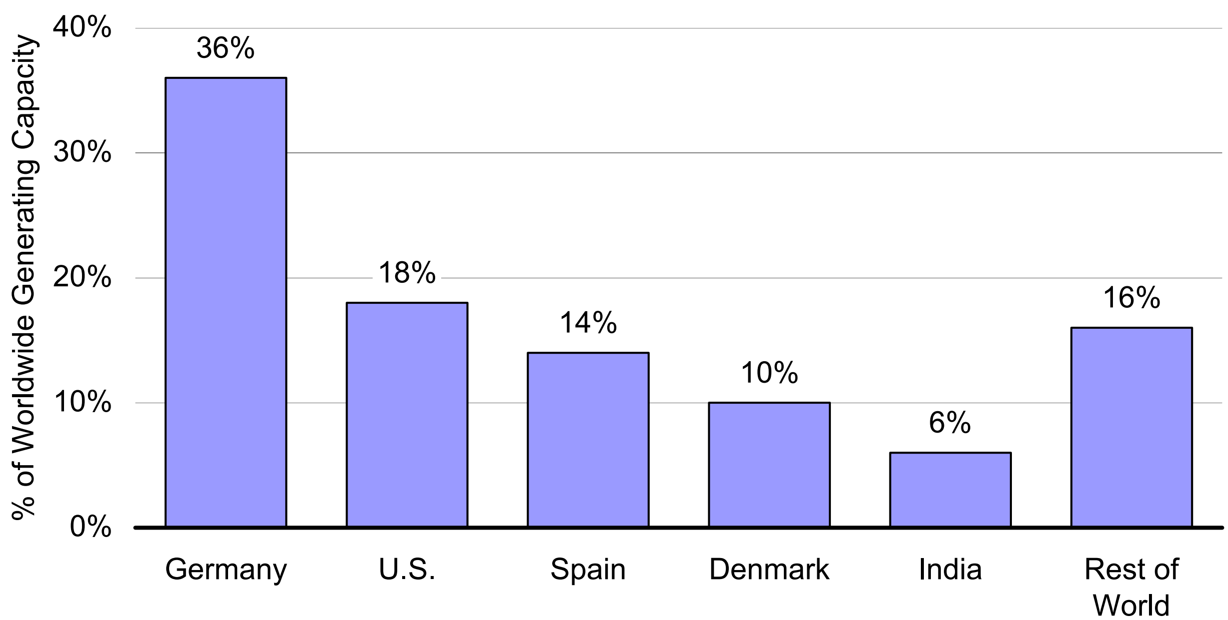
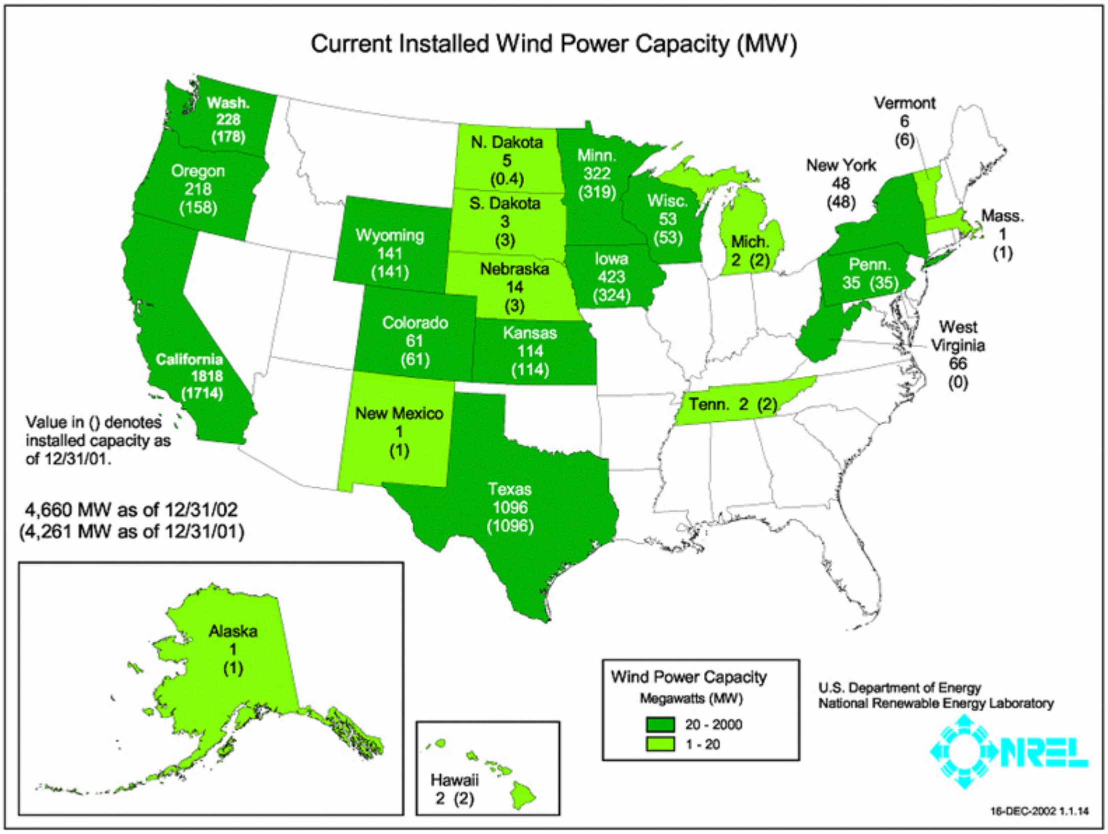


Figure 4. Distribution of Wind Power Generating Capacity Worldwide, 2001
Source: AWEA Global Wind Energy Market Report, March 2002

Figure 5. Wind Generating Capacity in the United States, 2001 and 2002



Source: U.S. Dept. of Energy, National Renewable Energy Laboratory (NREL)

History of Offshore Wind

The first offshore wind park, a five MW installation near Vindeby, Denmark, came online in 1991.[18] By the end of 2002, there were ten offshore wind farms in operation worldwide—all in Northern Europe—with a combined generating capacity of 250 MW. This represents a compound annual growth rate of 43%.[19] This development has been fueled largely by the presence of good wind resources in the North and Baltic Seas and by the availability of ever larger, more efficient turbines with which to tap this resource. “Mega” turbines, those that can generate 1 MW of power or greater, reached large-scale production in 1998, and today “multi-megawatt” turbines with capacities of 2.5 MW are being installed in some locations.[20]

ECONOMICS

Overview

While wind is a free resource, the systems used to capture the energy in the wind and convert it into electricity are not. Wind power production requires large capital outlays up-front, but does not incur fuel costs over the life of the plant. Wind producers also incur significant costs due to transmission infrastructure and regulatory frameworks that have been developed to suit the special characteristics of the fuels from which electricity has traditionally been produced—such as coal, nuclear and hydropower—but not wind. The many benefits of wind power accrue to producers, utilities and society. Benefits to utilities are discussed later in this section; benefits to society are discussed in the Environmental Impacts section below. Governments can help to spur wind development by revising regulations and providing financial incentives to wind power producers.

Cost Measures

The installed capital cost of a wind farm includes planning, equipment purchase and construction of the facilities. This cost, typically measured in $/kW, has decreased from more than $2,500/kW in the early 1980's to less than $1,000/kW for wind farms in the U.S. This decrease is due primarily to improvements in wind turbine technology, but also to the general increase in wind farm sizes. Larger wind farms benefit from economies of scale in all phases of a wind project from planning to decommissioning, as fixed costs can be spread over a larger total generating capacity.

Capital costs, which include the purchase of the turbine itself, construction of access roads and foundations, connecting to the grid and installation, account for about 70% of the total cost of energy. This is in contrast to fossil fuel-powered generation, which typically has lower up-front capital costs, but incurs fuel costs over the life of the system. Capital costs are now typically less than $1000 per kW of generating capacity for large wind farms.

Maintenance costs account for about 20% of the total cost of energy. Much of this is for unscheduled, but statistically predictable, maintenance. These costs increase steadily with increased wear and tear on the turbines. Since the amount of wear and tear is roughly proportional to the amount of power produced, maintenance costs are roughly proportional to energy production. A reasonable rule of thumb for large wind farms is $0.005/kWh.[21]

Property taxes, land use, insurance, transmission/wheeling, substation maintenance, and general & administrative costs together account for the remaining 10% of the total cost of energy.[22]

Levelized Cost

The levelized cost of energy, commonly expressed in cents/kWh, is the annual cost of recovering the total capital costs plus the recurring costs such as operations and maintenance and royalty payments divided by annual expected output. Table 1 (below) shows levelized costs for a 500 kW turbine, representative of a small-sized turbine for utility-scale applications.

Utility-scale wind farms in the U.S. produce wind power at a levelized cost of approximately two to six cents per kWh.[23] Cost varies due to differences in scale, quality of wind resource, and cost of financing. Cost of energy is the best of the three cost measures described here by which to compare the cost of wind power with the cost of electricity from other sources. However, while the cost of energy of a particular wind project is relatively straightforward, the comparison of the cost of wind generation to other types of generation is often controversial.

Table 1. Typical Levelized Cost of Energy for a Single 500 kW Turbine ($1997)

Cost of Energy Component	*Value (cents/kWh)*	*Percent of Total Cost of Energy*
Capital cost	3.08	70%
Unscheduled maintenance	0.68	16%
Preventive maintenance	0.18	4.1%
Major overhaul	0.04	0.92%
Other operating costs	0.39	8.9%
Total cost of Energy	**4.37**	**100%**

Source: National Wind Coordinating Committee[24]

Wind and natural gas generation were compared head-to-head in a 1999 decision by the State of Colorado Public Utility Commission (PUC) on choice of generation contracts to meet new load in the area served by Xcel Energy. Xcel had initially rejected wind contracts for 162 MW in favor of natural gas, based on assumptions of low natural gas costs, low capacity value for wind, and high wind ancillary service costs. However, after careful economic analysis the Colorado PUC found that wind "is justified on purely economic grounds, without weighing other benefits of wind generation that could be considered under the Integrated Resource Planning (IRP) rules."[25]

Specifically, the Colorado PUC found three important results to support the decision that the wind power bid was cost effective:

- New wind generation on Xcel's system is predicted to cost less than new gas-fired generation, assuming that gas costs are more than $3.50 per million cubic feet (mcf)
- For the 162 MW project, wind power receives a fair capacity value of 49 MW.
- Ancillary services to back up new wind power are not a major cost.

Variability and Grid Integration

Just as wind resources vary over time, demand for electricity fluctuates seasonally and over the course of the day. Utilities can, to a certain degree, predict peaks and troughs in demand and, since electricity is difficult to store, must arrange to secure just the right amount of power from generators at all times. Generally, this is done by having some plants run continuously at relatively constant output levels to meet what is called base load demand. These include primarily coal-fired, natural gas combined-cycle, hydropower and nuclear plants. Peaks in demand are satisfied by plants that can be more quickly turned on and off, such as natural-gas-fired simple-cycle plants.

Wind power is used when available to offset use of conventional fuels, which provides diversity in a utilities energy generation portfolio and a hedge against the impacts of natural gas price volatility. When and where wind resource peaks coincide with demand peaks, utilities benefit if they can use wind power to offset more expensive natural gas peak generation.

There has been criticism that the cost of integrating wind power into utility grids may be excessive due to the variable nature of the wind resource. However, according to the American Wind Energy Association (AWEA), costs are low at low levels of wind penetration in the grid. AWEA states that the technical limits of integration are reached when wind is providing about 40% or more of the total electricity on an annual basis. The economic costs of adding wind at low penetration levels are less than 0.2 cents/kWh, and at medium levels less than 0.2-0.5 cents/kWh. What is low and medium varies by application.[26]

Capacity Credit

The unresolved issue in cost comparisons between generating types is this: How should the cost of wind generated electricity be compared to coal and natural gas if wind is intermittent and the other resources are firm.

Electricity usage is measured in two ways: maximum usage at a point in time and total usage over time. Since electricity cannot be easily stored, utilities can only provide reliable service if they can serve both the maximum demand and the total usage likely to be placed on a system. They must, in addition, provide reserves to cover the unexpected outage of the largest units in the system plus unexpected outages affecting all units in a 10 even 20 year probability. For most systems reserves are 15% to 20% of expected peak demand.

The costs related to providing reliable service break down in the same two dimensions: capacity cost is the cost of meeting peak demand and energy cost is the cost of providing a KWh usage. Wind is an intermittent resource. Given good historical weather records we can say with some certainty what the expected annual output will be from a wind project. We cannot say with the same certainty what wind production will be at the time of peak demand. As the Colorado decision showed, it is clear that wind generation should receive some credit for providing capacity.

It is beyond the scope of this paper to do any more than note this debate and caution that comparisons between different generating sources are for total bus bar costs. The determination of the capacity credit for wind generation will be determined in regulatory proceedings.

Benefits to Utilities

The addition of wind power generation to the mix can provide economic benefit to power utilities.[27] Wind power can:

1. Help hedge against the volatile prices and uncertain availability of fossil fuels, as well as the uncertainty inherent in hydropower generation (due to variations in rainfall).
2. Be added incrementally, thus reducing the risk of incurring stranded costs due to excess capacity.
3. Provide generation capacity in geographic areas that are underserved by existing generation capacity. This can help to maintain proper voltage and current levels throughout the grid and reduce the need for upgrades to the transmission grid.

4. Help utilities to meet government-mandated Renewable Portfolio Standards (RPS).[28]
5. Serve as a hedge against future environmental regulations. In the past utilities could easily pass on to their customers any increased costs that they incurred due to the imposition of more stringent environmental regulations. This is not necessarily the case in today's competitive markets, where reducing exposure to regulatory risk may increase competitive advantage.
6. Provide an attractive product to customers who are seeking "green" power.

Economics of Offshore Wind

Two key factors differentiate offshore wind economics from those of onshore wind. The presence of stronger, less turbulent winds increases the revenue potential, while the location at sea increases construction and maintenance costs. These two factors tend to balance one another, resulting in a total cost of energy from offshore sites similar to that found at onshore sites.[29]

Capital costs at offshore sites are between 30 and 70% greater than at onshore sites, according to a British Wind Energy Association report published in 2000.[30] This is driven primarily by the high cost of building marine foundations, procuring installation equipment, and running submarine cables to carry the electricity to shore. However, these costs have decreased substantially in recent years, particularly because of improvements in foundation technology.[31] Operation and maintenance costs are also considerably higher because ships are needed to bring personnel and equipment to the turbines and a turbine may be inaccessible when the seas are rough.

As mentioned, these additional costs are balanced by the increased energy production possible at sea. In addition, because of the reduced wind shear encountered over water, offshore wind farms are being designed to last for 50 years, rather than the more common 20-25 year lifespan found on land. With a major refurbishment after 25 years, the greater investment required for an offshore wind park can be amortized over roughly twice as many years as a similar onshore park.

High energy prices, proximity to major population centers, and the presence of excellent wind resources in the North and Baltic Seas have fueled the development of offshore wind farms in Northern Europe. In contrast, the first offshore wind farms in the U.S. are still in the planning stages. Lower energy prices and the availability of good wind resources inland have delayed the development of offshore wind there. However, more than half of U.S. residents live in coastal counties[32], so offshore wind farms in these areas could avoid the higher transmission costs faced by wind farms in remote locations. In addition, several states in the densely populated Northeast, including New Jersey, Connecticut and Massachusetts, have established Renewable Portfolio Standards (RPS)[33], and wind may be one of the least-cost options available to meet these requirements.

ENVIRONMENTAL IMPACTS

Environmental Benefits

The environmental benefits of wind power are felt locally, regionally and globally. Wind power can displace power from fossil fuel-powered plants, and thereby help to improve local air quality, mitigate regional effects such as acid rain, and reduce greenhouse gas emissions. On average, each MWh of electricity generated in the U.S. results in the emission of 1,341 pounds of carbon dioxide (CO_2), 7.5 pounds of sulfur dioxide (SO_2) and 3.55 pounds of nitrogen oxides (NO_x).[34] Thus the 10 million MWh of electricity generated annually by U.S. wind farms represents about 6.7 million tons in avoided CO_2 emissions, 37,500 tons of SO_2 and 17,750 tons of NO_x.[35] This avoided CO_2 equals over 1.8 million tons of carbon, enough to fill 180 trains, each 100 cars long, with each car holding 100 tons of carbon every year.[36] Note that these figures are national averages and do not account for regional differences in fuel mix. Wind has the potential to displace relatively more emissions in areas where more heavily polluting fuels predominate.

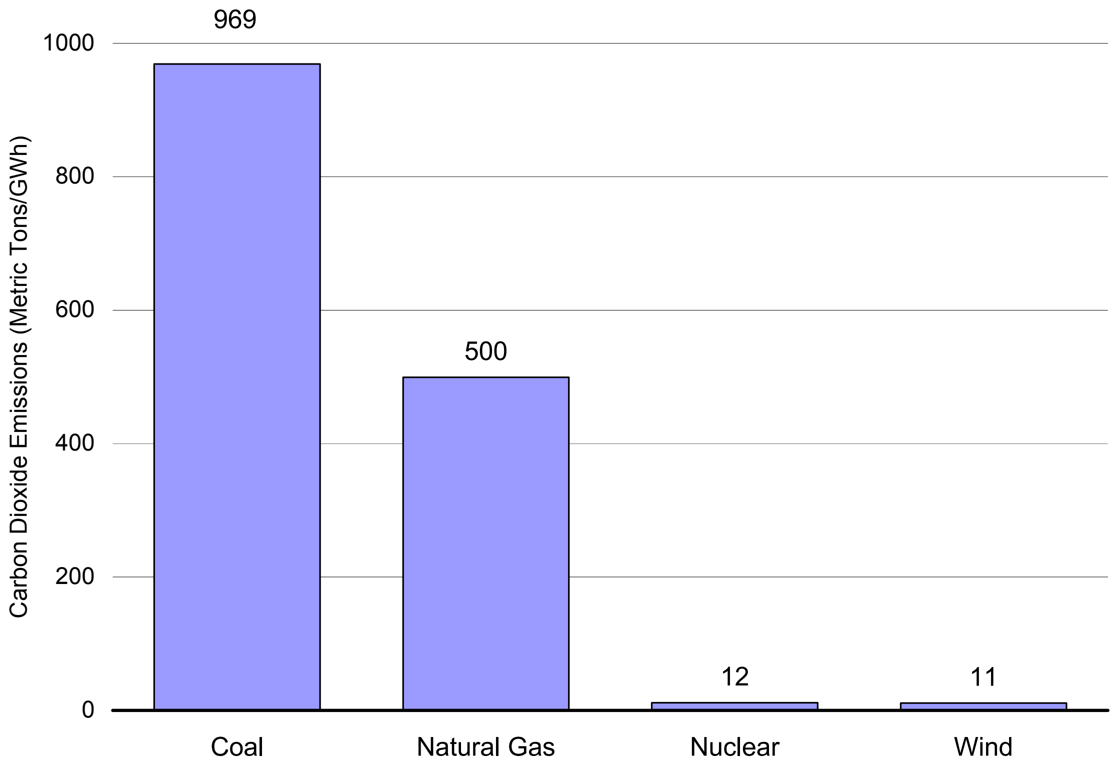
Power plants emit pollutants as a by-product of power generation, but also may account for further emissions in connection with plant construction, operation, and decommissioning. For example, the mining and transport of fuel are themselves energy-intensive activities, with associated emissions and environmental impacts. Wind compares favorably to traditional power generation on this metric as well: lifecycle CO_2 emissions per unit of power produced by a wind farm are about 1% of that for coal plants and about 2% of that for natural gas facilities (see Figure 7).[37]

Wind power is also comparatively energy efficient. The Energy Payback Ratio, a comprehensive measure of energy efficiency, is calculated by dividing the total amount of energy produced by a plant by the total energy consumed by the plant. One recent study calculated an Energy Payback Ratio of 23 for wind, 16 for nuclear, 11 for coal and 5 for natural gas.[38] This means that for each unit of energy put into building, maintaining and decommissioning a wind plant, for example, 23 units of electrical energy are obtained, on average.

Traditional power generation makes use of large amounts of water for the cooling of condensers and reactors and in mining processes. Overall, the power sector returns about 98% of the water it uses back to the source. However, much of this water is returned to lakes or streams containing heavy metals (from mining) or at significantly higher temperatures, causing damage to local ecosystems. In contrast, wind power makes use of small amounts of water, primarily for cleaning rotor blades.[39]

When a wind development is located on farm or range lands, the landowner typically receives royalties from the wind farm developer. One large wind turbine, occupying just a quarter acre of land, can provide approximately \$2000 to \$4500 in royalties annually. This income effectively increases the land's economic value and can provide the farmer with a hedge against crop price fluctuations. And the land can be used concurrently for both "wind farming" and conventional farming and ranching, since the wind turbines themselves occupy only about 5 to 15% of the land area encompassed by the wind farm.[40]

Figure 7. Life Cycle Carbon Dioxide Emissions, by Fuel



Sources: "Life Cycle Energy Cost of Wind and Gas-Turbine Power" by White, Radcliffe and Kulcinski, University of Wisconsin, 1999 (http://fti.neep.wisc.edu/FTI/POSTERS/sww_energy_ctr.pdf) and CA-OWEE, Final Report, Dec 2001, p7-1 (http://owe.starforze.net/ca-owee/indexpages/downloads/CA-OWEE_Complete.pdf)

As a result, wind developments can help expand rural tax bases and in some cases stave off urban development.[41]

These and other factors contribute to the positive environmental profile of wind power. A more detailed comparison of the environmental impacts of various power generation technologies is available in "The Environmental Imperative for Renewable Energy: An Update" by Adam Serchuk for Renewable Energy Policy Project, April 2000 (http://www.repp.org/repp_pubs/articles/envImp/envImp.pdf).

Environmental Concerns

The primary environmental concerns with wind power are related to potential visual, auditory, locational and wildlife impacts of windfarm installations. However, these concerns can be addressed through proper siting, public education, and the use of improved technologies.

Some are concerned by the visual impact of wind farms. On land, wind turbines are located where the wind resource is best—typically in highly visible, exposed locations. Offshore wind parks, likewise, are usually situated within sight of the shore. In both cases, the vertical towers and the motion of the rotors cause the wind turbines to become focal points in the landscape for observers close to the wind towers.[42] Fortunately, newer, larger rotors rotate more slowly than their predecessors, and thus are less eye-catching. To further mitigate the visual impact of wind turbines they can be painted to match their surroundings—NATO standard gray for offshore sites, for example.

Some of the wind energy captured by wind turbines is unavoidably transformed into sound energy. Air moving by the rotors generates sound, though improvements in rotor technology have greatly diminished the amount of sound produced in this way. Some sound may also emanate from the gearbox and generator, though sound absorbing materials are used to mitigate this. The apparent noise level of a typical wind farm at 350 meters distance varies between 35 and 45 dB(A). This is similar to the noise level in the reading room of a library. Keep in mind that a wind turbine produces no sound when it is not producing electricity, that is, below the "cut-in" speed. Above this speed, the amount of sound increases as the wind speed increases. Thus, wind farm noise will be partly masked by ambient noise, such as that from the wind rustling leaves or grasses. The sound also tends to be spread out across many frequencies, like white noise, further contributing to its unobtrusiveness. With proper considerations for sound propagation, wind turbines can be sited to have negligible noise impacts.[43]

Surveys indicate widespread public support for wind energy in countries where wind development has already taken place. However, proposed wind farms do sometimes encounter local opposition, especially in more densely populated areas. The above-mentioned issues—visual impact and sound—are the most commonly voiced concerns. This pattern of local opposition, known as NIMBY (Not In My Backyard), arises in response to many other forms of new development as well, including buildings, highways, airports, tunnels and other types of power plants. Research suggests that where the local population is educated on the benefits of wind power and is involved in the planning process, involved opposition is less.[44]

Concern arose when studies in the early 1990's documented the death of raptors from collisions with wind turbines in Altamont Pass, California. It was discovered that these turbines had been sited in the middle of prime raptor habitat. Extensive studies performed subsequently at sites around the U.S. measured only one or two bird deaths per turbine per year.[45] This is a small number, when contrasted with the estimated four to ten million birds that die each year in the U.S. from nighttime collisions with lighted telecommunications towers and the several hundred million more that die each year because of other human activities.[46] In addition, birds can see (and avoid) the newer, larger, more slowly rotating rotors more easily. Nevertheless, wind farms, and even individual turbines, should be carefully sited to avoid undue harm to birds.

Environmental Impacts at Sea

Developers of offshore wind farms must consider the potential impacts of the construction and operation of the wind turbines on sea life, including mammals, fish, plants and birds. The exact nature of these impacts will vary widely from site to site, due to the varied conditions found at sites around the world. Experience to date gives no strong indications of severe environmental impacts, though research on this subject is still sparse. For an excellent review of current knowledge regarding the environmental impacts of offshore wind farms, see chapter 7 of the final report of Concerted Action on Offshore Wind Energy in Europe, Dec. 2001.[47]

REGULATORY ISSUES

From permitting to transmission, government and industry regulations determine the rules for the electricity marketplace. These rules create the framework within which electricity is traded between generators, utilities and end-customers. They influence whether, where and what type of new plants are built. In some cases, these rules have been slow to change, giving unfair advantage to the traditional power generators that were in place when the rules were established, and unfairly penalizing newer forms of generation such as wind. These regulations, as well as government incentives (discussed in the next section), play a large role in determining how quickly wind power is adopted. Effective policies will help level the playing field and ensure that wind can compete fairly with other fuel sources in the electricity market.

Permitting Issues

An important part of any wind development project is securing the permits necessary to build and operate the proposed wind farm. Developers may be required to obtain permits from multiple jurisdictions, including local municipalities and counties, state agencies and the federal government. They must consider many factors, including soil erosion, air and water quality, birds and other wildlife, the view shed, public health and safety and the presence of archaeological resources. This permitting process may take from several months to several years to complete.[48] The vast majority of large wind projects subject to the National Environmental Protection Act (NEPA) have required only a *Finding of No Significant Impact*, and not a full-blown Environmental Impact Statement (EIS).

Offshore wind facilities in the U.S. face a similar permitting process, but it is less well defined and more uncertain, since no such facility has yet been approved. Individual states have authority over waters within three miles of their shores, and the federal government controls waters up to 200 miles out. Thus, projects situated in federal waters must obtain the approval of the Army Corps of Engineers, the lead regulatory agency for offshore wind projects in federal waters. They must also obtain approval from the appropriate state agencies for the cabling that will link the wind farm with the grid.[49] The U.S. Coast Guard must confirm that the wind turbines will not interfere with established shipping lanes and the U.S. Department of Interior (U.S. Fish and Wildlife Service) is involved with determining possible effects on fisheries.

The U.S. Department of Interior currently oversees all oil and natural gas exploration and commercial drilling operations in the Outer Continental Shelf. As of 2002, proposed legislation would put offshore wind farms under their authority as well, and would provide a transparent and uniform permitting process for offshore energy projects.[50]

Transmission Issues

Wind producers face significant challenges due to transmission infrastructure and related regulatory frameworks that have been developed to suit the special characteristics of traditional electricity production—coal, nuclear and hydropower—and not wind. Three characteristics of wind put it at a particular disadvantage vis-à-vis traditional generation sources: (1) it is supplied intermittently, (2) the best wind resources are often located far from where the electricity is needed, and (3) wind is a relatively new entrant to the electricity generation market.

As mentioned earlier, electric utilities must match supply with demand throughout the day. In order to ensure a reliable and predictable supply of power, they contract with power generators to provide pre-determined amounts of power according to fixed schedules. Regulatory penalties for deviation from these schedules are significant—anywhere from two to ten cents per kWh.[51] This system is predicated on the assumption that power plant operators can guarantee a certain output at some future time. However, this assumption is not valid for wind power plants, except in the case of short-term—hour-ahead or 10-minute-ahead—forecasts, which are reasonably accurate. The ability to perform these near-term forecasts makes it possible for wind to participate in real-time balancing markets, which can help address reliability concerns.

Most electricity demand is in urban areas. To reduce transmission costs, fossil and nuclear fuel-powered plants are typically situated close to urban areas and their fuels are transported to them. In contrast, good wind resources are often found far from urban areas, and cannot be transported. Electricity produced by wind plants located in these remote areas must be transmitted great distances to its users. In some cases, wind developers are required to pay for the additional transmission infrastructure required, thereby reducing the economic feasibility of proposed wind projects. Some utilities charge generators on a per-mile basis, resulting in wind generators having to shoulder a disproportionate share of transmission costs. In other cases, a wind plant may have to pay a separate fee for each of several transmission systems through which the power it generates passes on its way to the distant consumers. This is known as “rate pancaking” in the utility literature. Another common practice is to levy a transmission charge on generators based upon their *peak output* during a given period. Revenues, however, are more closely related to *average output*. This practice is reasonable when there is little difference between peak and average output levels, but unfairly penalizes wind plants, which often experience a large difference between peak and average output levels.

Wind’s status as a relatively new entrant to the electricity market also puts it at a disadvantage when competing for scarce transmission capacity. When the demand for a transmission path exceeds its reliable capacity, utilities react by limiting generation. Historically, they have allocated transmission capacity to those generators that have been in the market longest. When newer market entrants have been allowed to bid for constrained capacity, wind producers have been frustrated by their inability to accurately predict how much capacity they will need at a given hour on a given day in the future.

Impact of Emissions Regulations

Stricter emission regulations can improve wind power’s competitiveness by forcing fossil fuel-fired generating plants to internalize costs associated with their plants’ emissions. In the U.S., the Clean Air Act of 1970/1977 is the Federal law that regulates air emissions from power plants. It was amended in 1990 to improve on existing, and introduce new, programs to address acid rain, smog and other environmental problems.[52] These programs, by introducing pollution caps or providing disincentives to pollute, affect the mix of fuel sources used to generate electricity in the U.S.

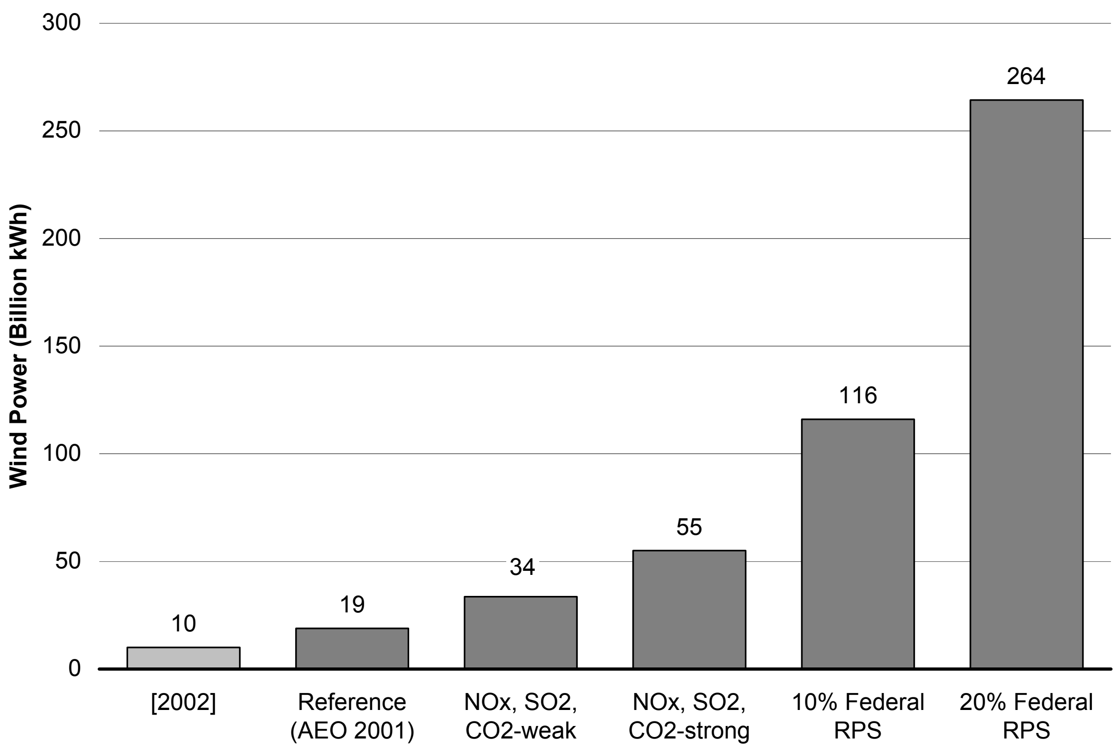
For example, U.S. EPA has set NO_x emissions caps for the most heavily polluting states. These states must devise State Implementation Plans (SIP) for meeting these goals, and these plans may include the use of energy efficiency and renewable energy offsets. Thus, in some states wind power can play an important role in limiting NO_x emissions and meeting EPA's requirements.[53] Incentives for limiting emissions can also be pursued indirectly, for example, by offering Production Tax Credits to those who produce emissions-free electricity.

Proposed changes to policy can be evaluated for their expected effects on the amount of wind power generated in the future. The U.S. Energy Information Administration (EIA) performed just such an analysis in 2001, at the request of the U.S. House of Representatives. In their reference case scenario, which takes into account the laws and regulations that were in place as of the end of August 2000, annual wind power generation increases almost twofold from 10 billion kWh today to 19 billion kWh in 2020. If NO_x and SO_2 regulations are strengthened, they forecast 34 billion kWh in 2020; and if, instead, a 20% Federal Renewable Portfolio Standard (RPS) is implemented, annual wind power generation is projected to climb to over 260 billion kWh in 2020 (see Figure 8).[54]

PROMOTING RENEWABLES

While wind power is approaching direct competitiveness with conventional electricity generation, governmental policies and incentives play an important role in helping to level the playing field and give wind a chance to compete fairly. Well-written and enforced policy addressing the issues outlined below will help wind power reach its full potential.

Figure 8. Electricity Generation from Wind in the U.S. Under Various EIA Emissions Policy Scenarios, 2020



Source: EIA and AWEA[55]

Subsidies

Government subsidies in the electricity industry have helped newer fuel sources to compete with traditional fossil fuel-powered plants, which often can produce electricity at lower cost to the producer. They can do so principally because the human health and environmental costs are largely externalized and born by society, creating a subsidy of sorts to fossil fuel burners. Subsidies, both direct and indirect, can reduce the effective cost of electricity from renewable energy sources, and thus increase sales. Direct subsidies consist of actual agency expenditures, including funds for research, technology development and regulation. Indirect or "off-budget" subsidies typically take the form of tax credits, interest rate discounts and insurance. Subsidies for renewable energy have often been proportionally less than those for conventional generation. For example, from 1947 to 1999, the U.S. government provided approximately $150 billion in total subsidies to nuclear, solar and wind electricity production and technologies. Less than 1% of this went to wind, while nuclear and solar received roughly 96% and 3% of the total, respectively.[56]

Tax Incentives

The federal Production Tax Credit (PTC) is the most significant U.S. policy driving wind power production. Those producing electricity from wind, closed-loop biomass and poultry waste receive 1.5 cents (adjusted for inflation) for each kWh produced during the first ten years of a plant's operation.[57] The federal PTC has been instrumental in spurring the development of wind power since its adoption in 1992. It was renewed in 1999, but was allowed to expire on December 31, 2001, creating uncertainty regarding the prospects for wind power in the U.S. On March 8, 2002, Congress passed legislation to extend the PTC to December 31, 2003, but its long-term future is still uncertain.[58]

This uncertainty is causing wind developers to incur added costs as they rush to get new plants online before PTC expiration. Many power analysts believe that uncertainty about the future economic viability of wind power is also causing under-investment in wind energy. In fact, the U.S. Energy Information Administration projects that were the PTC extended to cover plants coming on-line by the end of 2006, wind power generating capacity nationwide could be expected to increase to 13,000 MW by 2020, compared to 9,000 MW without the extension.[59]

Some U.S. states also provide tax incentives to wind developers. These incentives include investment tax credits, production tax credits, and property and sales tax incentives. The state investment tax credits have been found to lessen the value of the federal PTC, due to "double-dipping" provisions in the latter. The effect of other state incentives on the effective value of the federal PTC to producers is unclear.[60]

Renewable Portfolio Standards

A Renewable Portfolio Standard (RPS) requires that a certain minimum percent of all electricity generation be from renewables. As of 2002, twelve U.S. States have an enforceable RPS in place and another three have established voluntary renewable energy goals or have enacted RPS-type legislation without enforcement provisions.[61] A notable example of wind development spurred by an RPS is found in Texas, where a well-designed RPS combined with the Federal PTC resulted in the construction of more than ten wind projects in the first year, with a combined generating capacity of 930 MW.[62] Provisions for a federal RPS were contained in bills before both houses of the U.S. Congress in 2002, but no action has been taken to date.[63] The 108th Congress is expected to consider energy legislation when it convenes in early 2003, though it is uncertain whether an RPS would be included in any such legislation.

Public Benefit Funds

Several U.S. states have established Public Benefit Funds (PBF) to fund renewable energy, energy efficiency and other energy programs.[64] Typically, a small per-kWh charge—called a System Benefit Charge (SBC)—is added to residents' electricity bills to raise the needed funds. Many PBFs make funds available to promote wind development. In Illinois, for example, wind projects greater than 10 MW in size are eligible to have up to 10% of project costs ($2.75 million maximum) paid for out of the PBF. Smaller projects can have an even larger share of their project costs paid.[65] The Connecticut PBF has provided funding for a statewide wind energy study; and the state of California, through its PBF, can assist with the development and maintenance of existing wind power plants.[66]

FUTURE TRENDS

Decreasing Costs, Increasing Supply

The market for wind power generation is rapidly expanding, due largely to decreasing technological costs and the institution of government incentives, especially in Europe and the U.S. Approximately 6500 MW of new generating capacity was installed around the world in 2001, about 2600 MW of which was in Germany and nearly 1700 MW of which was in the U.S. These additions increased total global generating capacity by 37% from the 17,500 MW that existed at the end of 2000.[67] The Danish consultancy BTM Consult expects growth to continue at an average annual rate of 16% through 2006, reaching a total capacity of about 75,000 MW at that time, though political, technical and economic developments may combine to either over- or under-shoot this estimate.[68]

Several individual countries have committed to producing some significant portion of their electricity from wind in the coming years. Germany's goal is to produce 25% of its power from wind by 2030.[69] Canada aims to have 10,000 MW of generating capacity online by 2010,[70] and analysts expect India to have a generating capacity of at least 6,000 MW by then. The World Energy Council estimates that wind power generating capacity worldwide may total as much as 474,000 MW by the year 2020, though again time will tell whether this goal is met.

In the U.S., the Department of Energy's *Wind Powering America* initiative calls for wind to meet 5% of the country's electricity demand by 2020. However, the U.S. DOE Energy Information Administration's Reference Case Forecast projects that wind will meet only one tenth of that, or 0.5% of demand, by 2020.[71] Clearly, significant changes to "business as usual", including regulatory reforms and well-designed incentives, will be needed to meet the goals set by the *Wind Powering America* initiative.

While 1 to 2.5 MW turbines are increasingly common, 3 to 5 MW turbines are being developed, and may become common in the future.[72] Technological developments may also improve the economics of placing turbines in lower-class wind regimes (areas with lower wind speeds), significantly increasing wind power production potential worldwide.

While capital and operating costs are likely to continue to decrease as the wind industry continues to gain experience, utility-scale wind power expansion will continue to be strongly influenced by the scope and effectiveness of regulatory policy, as well as implicit and explicit power-generation subsidy and incentive structures. Concern about global warming and governments' commitments to reduce greenhouse gas emissions will likely increase the demand for "green" power. Wind power is a proven technology and is poised to help meet this increased demand in many countries.

Future of Offshore Wind

Offshore wind power generating capacity is expected to expand significantly in the coming years, especially in Northern Europe. The European Wind Energy Association (EWEA) has set a target of 50,000 MW of offshore wind capacity by 2020, one third of the total wind goal for Europe. The U.K., with the largest wind energy potential of any country in Europe, has identified 13 potential sites that could collectively offer a capacity of more than 1,000 MW.[73] Germany plans to obtain most of its wind power from offshore installations, with 20,000 to 25,000 MW of capacity targeted for 2025.[74] An Irish company, Airtricity, plans to begin construction in early 2003 of a 520 MW, 200-turbine wind farm in the Arklow Bank area of the Irish Sea.[75]

While Northern Europe enjoys substantial wind resources at relatively shallow water depths, the U.S. isn't as fortunate. Shallow waters (<100 feet deep) extend out for only a few miles from most of the East Coast, while the sea floor descends even more quickly along much of the West Coast. Tethered, floating platforms that could support multiple turbines at water depths of up to 1,000 feet are used by the oil and gas industries. However, their feasibility and cost-effectiveness in offshore wind farm development has not yet been proven.

As of late 2002, several offshore wind farms proposed for sites along the East Coast are under review. These include a wind farm off Cape Cod, Massachusetts proposed by Cape Wind Associates, LLC (discussed above) and 22 sites proposed by Winergy, LLC of Shirley, New York. The approval of one of these proposed wind farms would constitute a major milestone in the development of wind power in the U.S., as it could open the door to further offshore wind development.

NON-UTILITY-SCALE WIND POWER SYSTEMS

More than 99% of wind power generating capacity is part of large utility-scale plants that produce electricity for the retail market, with the remainder accounted for by smaller-scale installations. These smaller installations are referred to as "distributed" generation. Distributed wind installations, ranging in size from a single turbine with 100 kW generating capacity to a collection of turbines with a combined capacity of 12 MW, are designed to meet the power needs of a business, farmers cooperative, or small community.[76] Small wind systems, with less than 100 kW of generating capacity, are typically used to produce power for a single home.

Distributed Wind

Distributed wind projects are not directly connected to the transmission grid, but usually are connected to the local power distribution network, and as such can help to shore up the distribution grid in places where it is weak. The construction of a new one MW wind farm outside Seattle, Washington, for example, postponed the need for costly upgrades to transmission and distribution lines in the area. It also reduced line losses due to the very strong correlation between the available wind resource and the load on the distribution system.[77] An Oak Ridge National Laboratory review of seven case studies suggests that it is possible to add 50 to 100 MW of new wind generating capacity to supply local load in many areas, without needing to significantly upgrade the transmission system.[78]

Small Wind

About 15 MW of small wind (<100 kW) generating capacity exists in the U.S. today.[79] Many such systems are connected to the grid so that any excess electricity generated can be sold to the utility. In places where net metering is allowed, the utility purchases this electricity at the retail rate, effectively offsetting electricity purchased from the utility when the customer's electricity needs exceed the amount generated by the turbine. Where net metering is not required, excess electricity generated at the customer site is purchased by the utility at the lower wholesale rate or avoided cost of power production. Thus, net metering reduces the customer's total cost of electricity and makes on-site electricity generation more attractive to many electricity customers.

More information about small-scale wind can be found on the American Wind Energy Association (AWEA) web site (http://www.awea.org/smallwind.html) and on the *Wind Powering America* web site (http://www.eren.doe.gov/windpoweringamerica/small_wind.html), an initiative of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EREN).

CLOSING

We hope this paper has provided the reader with a balanced overview of the utility-scale wind power industry. We believe clean, reliable power can be developed from renewable resources, with wind power making an important contribution. Examples from the U.S. wind sector have been used to illustrate the costs, benefits, policies, and trends in wind energy today. What follows is a list or further resources available on the Web to allow the reader to gain a deeper understanding of the potential of wind power and the issues surrounding its development. We urge the reader to seek further understanding of these issues, and the means to their resolution, in order to support the progress of wind energy in providing clean, reliable, and economic power.

SOURCES OF FURTHER INFORMATION

General

- American Wind Energy Association http://www.awea.org
- Danish Wind Industry Association--Guided Tour on Wind Energy http://www.windpower.org/
- Energy Information Administration, U.S. Department of Energy http://www.eia.doe.gov
- National Wind Coordinating Council http://www.nationalwind.org
- National Wind Technology Center, National Renewable Energy Laboratory, U.S. Department of Energy http://www.nrel.gov/wind
- Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy http://www.eere.energy.gov/windpoweringamerica/

Offshore Wind

- The British Wind Energy Association http://www.offshorewindfarms.co.uk
- Offshore Windenergy in Europe http://www.offshorewindenergy.org
- Massachusetts Technology Collaborative http://www.masstech.org/RenewableEnergy/green_power/outreach/offshore_cape.htm

International Wind Trade Associations

- Australian Wind Energy Association http://www.auswea.com.au
- British Wind Energy Association http://www.britishwindenergy.co.uk/main.html
- Canadian Wind Energy Association http://www.canwea.ca
- Danish Wind Energy Association http://www.windpower.dk
- European Wind Energy Association http://www.ewea.org
- Irish Wind Energy Association http://www.iwea.com
- New Zealand Wind Energy Association http://www.windenergy.org.nz
- South African Wind Energy Association http://www.icon.co.za/~sawea/

ENDNOTES

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[8] *Guided Tour on Wind Energy.* Danish Wind Industry Association (http://www.windpower.org)
[9] "Floating Offshore Wind Energy" by Andrew R. Henderson and Minoo H. Patel, Department of Mechanical Engineering, University College London (http://www.owen.eru.rl.ac.uk/documents/bwea20_48.pdf) and "Hydrogen Production At Offshore Wind Farms" by Matthias Altmann and Frank Richert (http://www.hydrogen.org/wissen/pdf/GEO2001OffshoreH2.pdf)
[10] *Guided Tour on Wind Energy.* Danish Wind Industry Association (http://www.windpower.org)
[11] *Guided Tour on Wind Energy.* Danish Wind Industry Association (http://www.windpower.org)
[12] *Busbar cost* is the "at-the-gate" production cost, before transmission. This is similar to the *mine-mouth cost* of coal. AWEA web site (http://www.awea.org/faq/cost.html).
[13] *The Choice: An Energy Strategy for the 21st Century*, Worldwatch Institute news release, 15 May 2001 (http://www.worldwatch.org/alerts/010517.html)
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[16] AWEA Global Wind Energy Market Report, March 2002 (http://www.awea.org/pubs/documents/GlobalWEMarket2002.pdf)
[17] Wind Powering America web site, National Renewable Energy Laboratory, U.S. Dept. of Energy (http://www.eren.doe.gov/windpoweringamerica/wind_installed_capacity.html)
[18] *Concerted Action on Offshore Wind Energy in Europe*. British Wind Energy Association, 2001 (http://www.windenergy.citg.tudelft.nl/content/research/pdfs/bwea01_arh.pdf)
[19] Includes the ten plants that came online through 2002, including the new plant near Horns Rev, Denmark. CAGR=[(final amount - initial amount)^(1/number of time periods)]-1. The Average Annual Growth Rate (AAGR) is simply the average of the eleven year-on-year growth rates, and in this case is 56%. Sources: British Wind Energy Association (http://www.offshorewindfarms.co.uk/reports/faqs.html), The Journal of the Hydrographic Society (http://www.hydrographicsociety.org/Articles/journal/2002/105-1.htm) and Elsam company website: https://www.elsam.com/engelsk/nyheder/uk-presse-020828.htm.
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[24] From "Wind Energy Costs", part of the National Wind Coordinating Committee's *Wind Energy Series* (No. 11, Jan. 1997). Assumptions include power rating of 500 kW, installed capital cost of $1,000/kW, capacity factor of 28% and energy production of 1.226 million kWh/yr.
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[34] CO_2 figure reflects 1999 data and was taken from Department of Energy and Environmental Protection Agency: "Carbon Dioxide Emissions from the Generation of Electric Power in the United States", July 2000 (http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2emiss.pdf); SO_2 and NO_x figures reflect 1998 data and were taken from U.S. EPA's E-GRID2000 (Emissions & Generation Resource Integrated Database), Sept. 2001.
[35] Emissions calculations based on AWEA estimate of annual wind power production of 10 billion kWh (http://www.awea.org/utilityscale.html)
[36] A molecule of CO_2 is comprised of one molecule of carbon having atomic mass 12.01 and two molecules of oxygen, each having atomic mass 16.00. A typical open-top coal car has a 100-ton capacity.
[37] See sources for Figure 7. Note that life cycle carbon dioxide emissions for nuclear power may be considerably higher if the transport of radioactive wastes and electricity-intensive plutonium reprocessing (in the case of breeder reactors) are included.
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[52] U.S. EPA (http://www.epa.gov/history/topics/caa70/). See also REPP’s Issue Brief: “A Guide to the Clean Air Act for the Renewable Energy Community”, David Wooley, Feb 2002 (http://www.repp.org/articles/static/1/binaries/caaRen.pdf)
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[54] See source for Figure 8
[55] Figure for 2002 from AWEA. Projections for 2020 from “Analysis of Strategies for Reducing Multiple Emissions from Electric Power Plants: Sulfur Dioxide, Nitrogen Oxides, Carbon Dioxide, and Mercury and a Renewable Portfolio Standard”, July 2001, prepared at the request of the Subcommittee on National Economic Growth, Natural Resources, and Regulatory Affairs of the U.S. House of Representatives Committee on Government Reform (http://www.eia.doe.gov/oiaf/servicerpt/epp/). Reference Case based on the reference case for EIA’s Annual Energy Outlook 2001 (AEO2001). It incorporates the laws and regulations that were in place as of the end of August 2000, including the CAAA90 SO_2 emission cap and NO_x boiler standards and the 19-State summer season NO_x emission cap program—referred to as the “State Implementation Plan (SIP) Call” allowances.
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[60] "Analyzing the Interaction Between State Tax Incentives and the Federal Production Tax Credit for Wind Power". Ryan Wiser & Mark Bolinger. Berkeley Labs (http://eetd.lbl.gov/ea/EMS/reports/51465.pdf)
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