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Electric Power Generation: Nonconventional Methods

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Wind Power

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The wind is a free, clean, and inexhaustible energy source. It has served humankind well for many centuries by propelling ships and driving wind turbines to grind grain and pump water. Denmark was the first country to use wind for generation of electricity. The Danes were using a 23-m diameter wind turbine in 1890 to generate electricity. By 1910, several hundred units with capacities of 5 to 25 kW were in operation in Denmark (Johnson, 1985). By about 1925, commercial wind-electric plants using two- and three-bladed propellers appeared on the American market. The most common brands were Wincharger (200 to 1200 W) and Jacobs (1.5 to 3 kW). These were used on farms to charge storage batteries which were then used to operate radios, lights, and small appliances with voltage ratings of 12, 32, or 110 volts. A good selection of 32-VDC appliances was developed by the industry to meet this demand.

In addition to home wind-electric generation, a number of utilities around the world have built larger wind turbines to supply power to their customers. The largest wind turbine built before the late 1970s was a 1250-kW machine built on Grandpa's Knob, near Rutland, Vermont, in 1941. This turbine, called the Smith-Putnam machine, had a tower that was 34 m high and a rotor 53 m in diameter. The rotor turned an ac synchronous generator that produced 1250 kW of electrical power at wind speeds above 13 m/s.

After World War II, we entered the era of cheap oil imported from the Middle East. Interest in wind energy died and companies making small turbines folded. The oil embargo of 1973 served as a wakeup call, and oil-importing nations around the world started looking at wind again. The two most important countries in wind power development since then have been the U.S. and Denmark (Brower et al., 1993).

The U.S. immediately started to develop utility-scale turbines. It was understood that large turbines had the potential for producing cheaper electricity than smaller turbines, so that was a reasonable decision. The strategy of getting large turbines in place was poorly chosen, however. The Department of Energy decided that only large aerospace companies had the manufacturing and engineering capability to build utility-scale turbines. This meant that small companies with good ideas would not have the revenue stream necessary for survival. The problem with the aerospace firms was that they had no desire to manufacture utility-scale wind turbines. They gladly took the government's money to build test turbines, but when the money ran out, they were looking for other research projects. The government funded a number of test turbines, from the 100 kW MOD-0 to the 2500 kW MOD-2. These ran for brief periods of time, a few years at most. Once it was obvious that a particular design would never be cost competitive, the turbine was quickly salvaged.

Denmark, on the other hand, established a plan whereby a landowner could buy a turbine and sell the electricity to the local utility at a price where there was at least some hope of making money. The early

TABLE 1.1 Wind Power Installed Capacity

Canada	83
China	224
Denmark	1450
India	968
Ireland	63
Italy	180
Germany	2874
Netherlands	363
Portugal	60
Spain	834
Sweden	150
U.K.	334
U.S.	1952
Other	304
Total	9839

turbines were larger than what a farmer would need for himself, but not what we would consider utility scale. This provided a revenue stream for small companies. They could try new ideas and learn from their mistakes. Many people jumped into this new market. In 1986, there were 25 wind turbine manufacturers in Denmark. The Danish market gave them a base from which they could also sell to other countries. It was said that Denmark led the world in exports of two products: wind turbines and butter cookies! There has been consolidation in the Danish industry since 1986, but some of the companies have grown large. Vestas, for example, has more installed wind turbine capacity worldwide than any other manufacturer.

Prices have dropped substantially since 1973, as performance has improved. It is now commonplace for wind power plants (collections of utility-scale turbines) to be able to sell electricity for under four cents per kilowatt hour.

Total installed worldwide capacity at the start of 1999 was almost 10,000 MW, according to the trade magazine *Wind Power Monthly* (1999). The countries with over 50 MW of installed capacity at that time are shown in Table 1.1.

1.1 Applications

There are perhaps four distinct categories of wind power which should be discussed. These are

1. small, non-grid connected
2. small, grid connected
3. large, non-grid connected
4. large, grid connected

By small, we mean a size appropriate for an individual to own, up to a few tens of kilowatts. Large refers to utility scale.

1.1.1 Small, Non-Grid Connected

If one wants electricity in a location not serviced by a utility, one of the options is a wind turbine, with batteries to level out supply and demand. This might be a vacation home, a remote antenna and transmitter site, or a Third-World village. The costs will be high, on the order of $0.50/kWh, but if the total energy usage is small, this might be acceptable. The alternatives, photovoltaics, microhydro, and diesel generators, are not cheap either, so a careful economic study needs to be done for each situation.

1.1.2 Small, Grid Connected

The small, grid connected turbine is usually not economically feasible. The cost of wind-generated electricity is less because the utility is used for storage rather than a battery bank, but is still not competitive.

In order for the small, grid connected turbine to have any hope of financial breakeven, the turbine owner needs to get something close to the retail price for the wind-generated electricity. One way this is done is for the owner to have an arrangement with the utility called net metering. With this system, the meter runs backward when the turbine is generating more than the owner is consuming at the moment. The owner pays a monthly charge for the wires to his home, but it is conceivable that the utility will sometimes write a check to the owner at the end of the month, rather than the other way around. The utilities do not like this arrangement. They want to buy at wholesale and sell at retail. They feel it is unfair to be used as a storage system without remuneration.

For most of the twentieth century, utilities simply refused to connect the grid to wind turbines. The utility had the right to generate electricity in a given service territory, and they would not tolerate competition. Then a law was passed that utilities had to hook up wind turbines and pay them the avoided cost for energy. Unless the state mandated net metering, the utility typically required the installation of a second meter, one measuring energy consumption by the home and the other energy production by the turbine. The owner would pay the regular retail rate, and the utility would pay their estimate of avoided cost, usually the fuel cost of some base load generator. The owner might pay $0.08 to $0.15 per kWh, and receive $0.02 per kWh for the wind-generated electricity. This was far from enough to economically justify a wind turbine, and had the effect of killing the small wind turbine business.

1.1.3 Large, Non-Grid Connected

These machines would be installed on islands or in native villages in the far north where it is virtually impossible to connect to a large grid. Such places are typically supplied by diesel generators, and have a substantial cost just for the imported fuel. One or more wind turbines would be installed in parallel with the diesel generators, and act as fuel savers when the wind was blowing.

This concept has been studied carefully and appears to be quite feasible technically. One would expect the market to develop after a few turbines have been shown to work for an extended period in hostile environments. It would be helpful if the diesel maintenance companies would also carry a line of wind turbines so the people in remote locations would not need to teach another group of maintenance people about the realities of life at places far away from the nearest hardware store.

1.1.4 Large, Grid Connected

We might ask if the utilities should be forced to buy wind-generated electricity from these small machines at a premium price which reflects their environmental value. Many have argued this over the years. A better question might be whether the small or the large turbines will result in a lower net cost to society. Given that we want the environmental benefits of wind generation, should we get the electricity from the wind with many thousands of individually owned small turbines, or should we use a much smaller number of utility-scale machines?

If we could make the argument that a dollar spent on wind turbines is a dollar not spent on hospitals, schools, and the like, then it follows that wind turbines should be as efficient as possible. Economies of scale and costs of operation and maintenance are such that the small, grid connected turbine will always need to receive substantially more per kilowatt hour than the utility-scale turbines in order to break even. There is obviously a niche market for turbines that are not connected to the grid, but small, grid connected turbines will probably not develop a thriving market. Most of the action will be from the utility-scale machines.

Sizes of these turbines have been increasing rapidly. Turbines with ratings near 1 MW are now common, with prototypes of 2 MW and more being tested. This is still small compared to the needs of a utility, so clusters of turbines are placed together to form wind power plants with total ratings of 10 to 100 MW.

1.2 Wind Variability

One of the most critical features of wind generation is the variability of wind. Wind speeds vary with time of day, time of year, height above ground, and location on the earth's surface. This makes wind generators into what might be called energy producers rather than power producers. That is, it is easier to estimate the energy production for the next month or year than it is to estimate the power that will be produced at 4:00 PM next Tuesday. Wind power is not dispatchable in the same manner as a gas turbine. A gas turbine can be scheduled to come on at a given time and to be turned off at a later time, with full power production in between. A wind turbine produces only when the wind is available. At a good site, the power output will be zero (or very small) for perhaps 10% of the time, rated for perhaps another 10% of the time, and at some intermediate value the remaining 80% of the time.

This variability means that some sort of storage is necessary for a utility to meet the demands of its customers, when wind turbines are supplying part of the energy. This is not a problem for penetrations of wind turbines less than a few percent of the utility peak demand. In small concentrations, wind turbines act like negative load. That is, an increase in wind speed is no different in its effect than a customer turning off load. The control systems on the other utility generation sense that generation is greater than load, and decrease the fuel supply to bring generation into equilibrium with load. In this case, storage is in the form of coal in the pile or natural gas in the well.

An excellent form of storage is water in a hydroelectric lake. Most hydroelectric plants are sized large enough to not be able to operate full-time at peak power. They therefore must cut back part of the time because of the lack of water. A combination hydro and wind plant can conserve water when the wind is blowing, and use the water later, when the wind is not blowing.

When high-temperature superconductors become a little less expensive, energy storage in a magnetic field will be an exciting possibility. Each wind turbine can have its own superconducting coil storage unit. This immediately converts the wind generator from an energy producer to a peak power producer, fully dispatchable. Dispatchable peak power is always worth more than the fuel cost savings of an energy producer. Utilities with adequate base load generation (at low fuel costs) would become more interested in wind power if it were a dispatchable peak power generator.

The variation of wind speed with time of day is called the diurnal cycle. Near the earth's surface, winds are usually greater during the middle of the day and decrease at night. This is due to solar heating, which causes "bubbles" of warm air to rise. The rising air is replaced by cooler air from above. This thermal mixing causes wind speeds to have only a slight increase with height for the first hundred meters or so above the earth. At night, however, the mixing stops, the air near the earth slows to a stop, and the winds above some height (usually 30 to 100 m) actually increase over the daytime value. A turbine on a short tower will produce a greater proportion of its energy during daylight hours, while a turbine on a very tall tower will produce a greater proportion at night.

As tower height is increased, a given generator will produce substantially more energy. However, most of the extra energy will be produced at night, when it is not worth very much. Standard heights have been increasing in recent years, from 50 to 65 m or even more. A taller tower gets the blades into less turbulent air, a definite advantage. The disadvantages are extra cost and more danger from overturning in high winds. A very careful look should be given the economics before buying a tower that is significantly taller than whatever is sold as a standard height for a given turbine.

Wind speeds also vary strongly with time of year. In the southern Great Plains (Kansas, Oklahoma, and Texas), the winds are strongest in the spring (March and April) and weakest in the summer (July and August). Utilities here are summer peaking, and hence need the most power when winds are the lowest and the least power when winds are highest. The diurnal variation of wind power is thus a fairly good match to utility needs, while the yearly variation is not.

The variability of wind with month of year and height above ground is illustrated in Table 1.2. These are actual wind speed data for a good site in Kansas, and projected electrical generation of a Vestas turbine (V47-660) at that site. Anemometers were located at 10, 40, and 60 m above ground. Wind

TABLE 1.2 Monthly Average Wind Speed in MPH and Projected Energy Production at 65 m, at a Good Site in Southern Kansas

Month	10 m Speed	60 m Speed	Energy (MWh)	Month	10 m Speed	60 m Speed	Energy (MWh)
1/96	14.9	20.3	256	1/97	15.8	21.2	269
2/96	16.2	22.4	290	2/97	14.7	19.0	207
3/96	17.6	22.3	281	3/97	17.4	22.8	291
4/96	19.8	25.2	322	4/97	15.9	20.4	242
5/96	18.4	23.1	297	5/97	15.2	19.8	236
6/96	13.5	18.2	203	6/97	11.9	16.3	167
7/96	12.5	16.5	169	7/97	13.3	18.5	212
8/96	11.6	16.0	156	8/97	11.7	16.9	176
9/96	12.4	17.2	182	9/97	13.6	19.0	211
10/96	17.1	23.3	320	10/97	15.0	21.1	265
11/96	15.3	20.0	235	11/97	14.3	19.7	239
12/96	15.1	20.1	247	12/97	13.6	19.5	235

speeds at 40 and 60 m were used to estimate the wind speed at 65 m (the nominal tower height of the V47-660) and to calculate the expected energy production from this turbine at this height. Data have been normalized for a 30-day month.

There can be a factor of two between a poor month and an excellent month (156 MWh in 8/96 to 322 MWh in 4/96). There will not be as much variation from one year to the next, perhaps 10 to 20%. A wind power plant developer would like to have as long a data set as possible, with an absolute minimum of one year. If the one year of data happens to be for the best year in the decade, followed by several below average years, a developer could easily get into financial trouble. The risk gets smaller if the data set is at least two years long.

One would think that long-term airport data could be used to predict whether a given data set was collected in a high or low wind period for a given part of the country, but this is not always true. One study showed that the correlation between average annual wind speeds at Russell, Kansas, and Dodge City, Kansas, was 0.596 while the correlation between Russell and Wichita was 0.115. The terrain around Russell is very similar to that around Wichita, and there is no obvious reason why wind speeds should be high at one site and low at the other for one year, and then swap roles the next year.

There is also concern about long-term variation in wind speeds. There appears to be an increase in global temperatures over the past decade or so, which would probably have an impact on wind speeds. It also appears that wind speeds have been somewhat lower as temperatures have risen, at least in Kansas. It appears that wind speeds can vary significantly over relatively short distances. A good data set at one location may underpredict or overpredict the winds at a site a few miles away by as much as 10 to 20%. Airport data collected on a 7-m tower in a flat river valley may underestimate the true surrounding hilltop winds by a factor of two. If economics are critical, a wind power plant developer needs to acquire rights to a site and collect wind speed data for at least one or two years before committing to actually constructing turbines there.

1.2.1 Land Rights

Spacing of turbines can vary widely with the type of wind resource. In a tradewind or a mountain pass environment where there are only one or two prevailing wind directions, the turbines can be located "shoulder to shoulder" crossways to the wind direction. A downwind spacing of ten times the rotor diameter is usually assumed to be adequate to give the wind space to recover its speed. In open areas, a crosswind spacing of four rotor diameters is usually considered a minimum. In the Great Plains, the prevailing winds are from the south (Kansas, Oklahoma, and Texas) or north (the Dakotas). The energy in the winds from east and west may not be more than 10% of the total energy. In this situation, a spacing of ten rotor diameters north–south and four rotor diameters east–west would be minimal. Adjustments would be made to avoid roads, pipelines, power lines, houses, ponds, and creeks.

The results of a detailed site layout will probably not predict much more than 20 MW of installed capacity per square mile (640 acres). This figure can be used for initial estimates without great error. That is, if a developer is considering installing a 100-MW wind plant, rights to at least five square miles should be acquired.

One issue that has not received much attention in the wind power community is that of a fair compensation to the land owner for the privilege of installing wind turbines. The developer could buy the land, hopefully with a small premium. The original deal could be an option to buy at some agreed upon price, if two years of wind data were satisfactory. The developer might lease the land back to the original landowner, since the agricultural production capability is only slightly affected by the presence of wind turbines. Outright purchase between a willing and knowledgeable buyer and seller would be as fair an arrangement as could be made.

But what about the case where the landowner does not want to sell? Rights have been acquired by a large variety of mechanisms, including a large one-time payment for lease signing, a fixed yearly fee, a royalty payment based on energy produced, and combinations of the above. The one-time payment has been standard utility practice for right-of-way acquisitions, and hence will be preferred by at least some utilities. A key difference is that wind turbines require more attention than a transmission line. Roads are not usually built to transmission line towers, while they are built to wind turbines. Roads and maintenance operations around wind turbines provide considerably more hassle to the landowner. The original owner got the lease payment, and 20 years later the new owner gets the nuisance. There is no incentive for the new landowner to be cooperative or to lobby county or state officials on behalf of the developer.

A one-time payment also increases the risk to the developer. If the project does not get developed, there has been a significant outlay of cash which will have no return on it. These disadvantages mean that the one-time payment with no yearly fees or royalties will probably not be the long-term norm in the industry.

To discuss what might be a fair price for a lease, it will be helpful to use an example. We will assume the following:

- 20 MW per square mile
- Land fair-market value \$500/acre
- Plant factor 0.4
- Developer desired internal rate of return 0.2
- Electricity value \$0.04/kWh
- Installed cost of wind turbine \$1000/kW

A developer that purchased the land at \$500/acre would therefore want a return of \$(500) (0.2) = \$100/acre. America's cheap food policy means that production agriculture typically gets a much smaller return on investment than the developer wants. Actual cash rent on grassland might be \$15/acre, or a return of 0.03 on investment. We see an immediate opportunity for disagreement, even hypocrisy. The developer might offer the landowner \$15/acre when the developer would want \$100/acre if he bought the land. This hardly seems equitable.

The gross income per acre is

$$I = \frac{(20{,}000\ \text{kW})\ (0.4)\ (8760\ \text{hours/year})\ (\$0.04)}{640\ \text{acres}} = \$4380/\text{acre/year} \tag{1.1}$$

The cost of wind turbines per acre is

$$CT_a = \frac{(20{,}000\ \text{kW})\ (\$1000/\text{kW})}{640\ \text{acres}} = \$31{,}250/\text{acre} \tag{1.2}$$

We see that the present fair-market value for the land is tiny compared with the installed cost of the wind turbines. A lease payment of $100/acre/year is slightly over 2% of the gross income. It is hard to imagine financial arrangements so tight that they would collapse if the landowner (either rancher or developer) were paid this yearly fee. That is, it seems entirely reasonable for a figure like 2% of gross income to be a starting point for negotiations.

There is another factor that might result in an even higher percentage. Landowners throughout the Great Plains are accustomed to royalty payments of 12.5% of wholesale price for oil and gas leases. This is determined independently of any agricultural value for the land. The most worthless mesquite in Texas gets the same terms as the best irrigated corn ground in Kansas. We might ask if this rate is too high. A royalty of 12.5% of wholesale amounts to perhaps 6% of retail. Cutting the royalty in half would have the potential of reducing the price of gasoline about 3%. In a market where gasoline prices swing by 20%, this reduction is lost in the noise. If a law were passed which cut royalty payments in half, it is hard to argue that it would have much impact on our gasoline buying habits, the size of vehicles we buy, or the general welfare of the nation.

One feature of the 12.5% royalty is that it is high enough to get most oil and gas producing land under lease. Would 6.25% have been enough to get the same amount of land leased? If we assumed that some people would sign a lease for 12.5% that would not sign if the offer were 6.25%, then we have the interesting possibility that the supply would be less. If we assume the law of supply and demand to apply, the price of gasoline and natural gas would increase. The possible increase is shear speculation, but could easily be more than the 6.25% that was "saved" by cutting the royalty payment in half.

The point is that the royalty needs to be high enough to get the very best sites under lease. If the best site produces 10% more energy than the next best, it makes no economic sense to pay a 2% royalty for the second best when a 6% royalty would get the best site. In this example, the developer would get 10% more energy for 4% more royalty. The developer could either pocket the difference or reduce the price of electricity a proportionate amount.

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