

HIGH CAPACITY FACTOR WIND ENERGY SYSTEMS

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ABSTRACT

Wind generated electricity can be fundamentally transformed from an intermittent resource to a baseload power supply. For the case of long distance transmission of wind electricity, this change can be achieved at a negligible increase or even a decrease in the per unit cost of electricity. The economic and technical feasibility of this process can be illustrated by studying the example of a wind farm located in central Kansas and a 2000 km, 2000 megawatt transmission line to southern California. Such a system can have a capacity factor of 60 percent, with no economic penalty and without storage. With compressed air energy storage (CAES) (and with a negligible economic penalty), capacity factors of 70-95 percent can be achieved. This strategy has important implications for the development of wind energy throughout the world since good wind resources are usually located far from major demand centers.

INTRODUCTION

At present, most wind energy development has occurred in regions with excellent wind resources that are close to load centers, where transmission costs are low and transmission capacity is adequate. In the future, wind farms will be located far from load centers, and transmission cost and availability may constrain development. Also, as a consequence of the passage of the National Energy Policy Act of 1992, utilities are being required to separate transmission from generation and distribution charges. These factors indicate that it is important to consider wind farms and transmission lines as a system rather than as separate entities, and to minimize the cost of delivered electricity, including transmission cost.

Minimizing the cost of delivered electricity will entail increasing the system capacity factor. This has the added benefit of weakening an important objection often raised by utilities to renewable energy resources such as photovoltaic and wind systems. These are intermittent: that is they have a low capacity factor and a high forced outage rate. Increasing the capacity factor effectively reduces the intermittent characteristic of the resource. In addition, for a given transmission capacity, wind developers will be able to sell much more energy at no increase in the delivered per unit cost, increasing revenues and profits. Both utilities and wind farm developers will benefit from this approach.

Since a utility is accustomed to control, or dispatch, its sources of energy to meet demand at a given time, coping with intermittent generating technologies presents conceptual difficulties and operational challenges. These challenges certainly exist: the theoretical result that at low (<10 percent) system penetration an intermittent supply can be regarded as a negative load and effectively integrated, while completely correct (Haslett and Diesendorf, 1981; Grubb, 1991), does not give any indication of these problems (Friis and Mogens, 1993; Harrison, 1993).

In order to understand how it is possible to construct, with a minimum economic penalty, a high capacity factor system or a wind energy baseload system from an

intermittent resource, we shall first examine some of the characteristics of wind that influence the wind turbine capacity factor, and then some aspects of transmission line technology. Next, the concept will be illustrated by examining the economic and technical characteristics of a wind farm in western Kansas coupled to a 2000 km transmission line. Finally, the economic and technical attributes of a hybrid system consisting of a wind farm with compressed air energy storage (CAES) using the same transmission line will be examined. This type of system could, for example, replace the nuclear power plants at Diablo Canyon, CA, (2x1100 MW_e, average capacity factor - 76 percent) around the year 2010, at which time they would have been in operation for 25 years.

WIND AND WIND TURBINE CHARACTERISTICS

The amount of power generated by a wind turbine is a result of both the design characteristics of the turbine and the properties of the wind resource (the wind speed probability density as a function of wind velocity, $f(v)$). It has been found that the wind frequency can best be described by a Weibull probability distribution; $f(v)$ can be written as (Johnson, 1985):

Here c and k are the scale and shape factors, respectively. The parameter c has dimensions of velocity and is about 1.1 times the average wind velocity, while k largely determines the shape of $f(v)$. A k value close to 1 indicates a highly variable wind regime, while a k greater than 3 indicates more regular, steadier winds. Since detailed information on the wind frequency is often lacking, a k factor of 2 is often assumed in evaluating a wind resource. As will be shown, this can lead to a significant error in the

estimate of the capacity factor and the cost of electricity.

The power output (P_{out}) of a wind turbine as a function of wind velocity is written as:

The average power output (\bar{P}) of a wind turbine can be written as:

This is just the power output of the wind turbine at a given velocity times the frequency at which that velocity occurs, summed over all possible velocities.

The integral in Eq. 3 is the ratio of the average turbine output to the maximum turbine output and is defined as the wind turbine capacity factor (WTCF). In Figure 1 the capacity factor of a Vestas V27 wind turbine is plotted as a function of k for a constant wind power density of 440 W/m^2 , which is typical of that found over large areas of the Great Plains. The published characteristics of the Vestas V27-225 wind turbine (Vestas, 1993), an efficient 225 kW pitch regulated machine with high and low speed generators, and Eq. 1, were used in Eq. 3 to calculate the capacity factor. This shows clearly the importance of a detailed understanding of the wind resource. Typical values of k obtained from data taken in the Department of Energy (DOE) Candidate Wind Turbine Test Site program (Cavallo, 1994) are 2.4 to 3 at 50 m elevation over the Great Plains. If k is equal to 3, the capacity factor is 20 percent greater than at the usually assumed value of $k=2$, implying a correspondingly larger output per machine, and correspondingly lower costs per unit of output.

The wind resources of the U.S. have been evaluated using data from a wide variety of

sources (Elliott, 1987). Using the results of this survey, the wind electric potential of the U.S. has been estimated (Elliott, 1991) at $1200 \text{ GW}_{\text{avg}}$; more than 90 percent of this potential is located in the Great Plains, far from electricity demand centers. If these resources are to be utilized on a significant scale, long distance transmission lines will certainly be an integral part of the development.

We have chosen western Kansas for our wind farm location because, based on DOE data from this area, the Weibull K factor at 50 m is about 3 and the yearly average as well as the summer average wind power density is about 440 W/m^2 ; the former indicates an economically viable resource, while the latter indicates that system output will be high in the summer, when utility demand is highest. (Other Great Plains regions experience at least a 20 percent decrease in wind power density during the summer season.) Therefore, the wind regime assumed for these calculations is one with $P_w=440 \text{ W/m}^2$ and $k=3$, and is constant over the year; this represents a realistic best case scenario. It is also assumed that the wind turbine hub height is 50 m.

TRANSMISSION LINE TECHNOLOGY

For this case study, we have chosen high voltage direct current (HVDC) technology for the transmission line. This has been shown to be the lowest cost option for point to point power transfers over distances greater than about 800 km (Wu, 1990). There would initially be a significant difference between transmission line capacity and the output of the wind farm; in order to illustrate the general principles involved, overnight construction of all system components is assumed.

The cost estimates used here are based on those incurred in the construction of a 2000 MW, 450 kV, 2222 A, 1500 km HVDC transmission line between the La Grande hydroelectric complex at James Bay, Québec, and Boston, MA (Reason, 1990) as well as on information given by Long (1987). The agreement to build the HQ (Hydro Québec)

line was signed in 1983, and construction proceeded in two phases; the line was completed at the end of 1990. Long development times are typical for such projects: Watkins (1991) estimated an 8-12 year development time for the 3000 MW, 1100 km HVAC Pacific Northwest line. Although construction time was projected to be only 2.5 years, preparation of applications and the environmental impact statement, and hearings before various state agencies and commissions lengthened the total project time considerably. This indicates that such projects will require strong utility and governmental leadership.

The HQ transmission line was built over an existing right of way in the US, while in Québec the right of way had to be acquired and extensive road construction was necessary. According to project engineers, the transmission line cost about \$0.62 million per km (\$1 million per mile) both in the U.S. and in Québec. The cost of the converter stations (345 kV AC to 450 kV DC), filters and circuit breakers in the US was \$320 million. Converter losses are 0.6% per station; line resistance is 12 Ω per pole (the line has two conductors or poles, operating at +450 kV and -450 kV) so that total ohmic and conversion loss at full power is 140 MW, or 7 percent of the transmitted power. Operation and maintenance costs for the line are negligible.

The cost of the HQ transmission line (\$682/kV-km) is substantially greater than the HVDC line only costs (\$198-229/kV-km) cited by Long (1987). However, the HVAC transmission line cost of \$560/kV-km quoted by Watkins (1991) agrees well with that given by Long (\$576-607/kV-km for HVAC single circuit transmission lines). It may be that construction costs in the Quebec wilderness and New England are substantially greater than what would be encountered in the Great Plains, and therefore the HQ figures should be considered quite pessimistic.

HVDC converter costs of about \$110/kW are also quoted by Long (1987), and are significantly less than the \$160/kW for the HQ system. The latter, however, includes substantial AC and DC filter and shunt capacitor bank costs, which could account for the

difference.

WIND FARM-TRANSMISSION LINE SYSTEM

The conventional approach to the transmission of wind-generated electricity (Watkins, 1991) is to match the peak output of the wind farm to that of the transmission line. For our example, the transmission line capacity is 2000 MW, and the number (N) of wind turbines in the wind farm is:

$$N \cdot P_{\max} = 2000 \text{ MW.} \quad (4)$$

The capacity factor of this system is thus the capacity factor of the wind farm, which is the wind turbine capacity factor reduced by the average array and other losses. For the Vestas V27-225 (P_{\max} of 225 kW), the number of wind turbines needed in the baseline wind farm is 8,900. The wind turbine capacity factor, assuming $P_w=440 \text{ W/m}^2$ and a $k=2$ wind frequency regime, is 34.3 percent. If the average array and other losses (A) (Elliott 1994) are assumed to be 12 percent for a wind turbine spacing of 10 rotor diameters (D) in the direction of the prevailing wind and 5 diameters crosswind (10Dx5D), the wind farm capacity factor, and thus the system capacity factor, is then 30.2 percent.

There are three ways to increase the system capacity factor. The first is to locate the wind farm in an area of steady winds. The capacity factor quoted above makes the conventional assumption (SERI,1990) of a Rayleigh wind speed distribution (Weibull k factor of 2). If, for the same wind power density, the k factor is higher, the capacity factor is also greater: for the wind regime assumed here ($P_w=440 \text{ W/m}^2$, $k=3$) the wind turbine capacity factor is 41 percent and the wind farm capacity factor is 36 percent.

The second way to increase the system capacity factor is to increase the number of wind turbines in the wind farm above what is assumed in the conventional, or baseline,

approach (Cavallo, 1992; Cavallo, 1993). This will be referred to as an oversized wind farm. The additional turbines produce more power when the wind speed is below the rated turbine wind speed but where the winds blow most frequently. At higher wind velocities, some of the wind turbines must be shut down due to the limited capacity of the transmission line. However, since these higher wind velocities occur less frequently, the net result is an increase in the average power transmitted. The increased cost of the additional wind turbines is counterbalanced by a decrease in the per unit transmission cost.

The number of wind turbines in an oversized wind farm is calculated from Eq. 5:

$$(1-A) \cdot N \cdot P_{\max} = 2000 \text{ MW}, \quad (5)$$

where $(1-A)=0.88$ and P_{\max} is the turbine output at which the wind farm output is equal to the transmission line capacity.

The number of wind turbines is first increased from 8900 to 10100 (see Figure 1) to compensate for array and other losses; system capacity factor increases from 0.36 to 0.41 percent. As the number of wind turbines is increased further, P_{\max} begins to decrease: with 12600 wind turbines, P_{\max} is equal to 180 kW. The average power output for wind turbines in the oversized wind farm is calculated using Eq. 3 with $P_{\max}=180$ kW: for this case P_{avg} decreases by about 4.3 percent, and the system capacity factor increases by 20 percent, from 0.41 to 0.49. Thus, large gains in capacity factor are possible at a small sacrifice in average turbine output. The number of wind turbines can be increased in this fashion until the desired capacity factor at an acceptable cost of electricity is attained. The economic consequences of this development strategy will be examined in the next section.

Finally, storage can be added to the system to utilize the energy that would normally be lost when the output of the oversized wind farm exceeds the capacity of the transmission

line.

Cost of Electricity

The cost of electricity from a wind farm-transmission line system (in 1992\$) coming on line around the year 2010 can be computed as follows.

The wind turbine levelized cost is:

Here N is the number of wind turbines in the wind farm, ICC is the installed capital cost, assumed to be \$700/kW (1992\$)(Miller,1994) times 225 kW, the maximum output power of the Vestas V27-225. The capital charge rate CCR is taken to be 0.107 (EPRI TAG rule,1989), 8766 is the average number of hours in a year, and the array and other losses (A) are assumed to be 12 percent. The average turbine output power is computed using Eq. 3 for a $k=3$ wind regime with a wind power density of 440 W/m^2 .

Wind turbine operation and maintenance costs (O&M) are generally taken to be \$0.01/kWh for current technology (Lynette, 1989). Advances in wind turbine technology (variable speed, direct drive generator), as exemplified by the 500 kW Enercon E-40 machine (Enercon, 1993), should reduce this to less than \$0.005/kWh (SERI, 1990), the amount assumed in this analysis. In addition, a royalty of 4 percent of the busbar cost of electricity is assumed to be paid to the landowner.

The cost of energy from the wind farm (WFLC) is then:

$$\text{WFLC} = \text{WTLC} + \text{O\&M} + \text{Royalty.} \quad (7)$$

The transmission line levelized cost (TMLC) is:

Here TMCC is the installed capital cost of the transmission system, conservatively assumed to be \$1,520 million (1992\$) (line only cost is \$682/kV-km, 450 kV converter stations - \$320 million). The system capacity factor (CF) is no longer necessarily equal to the wind turbine capacity factor, but can in fact be much larger.

The levelized cost of transmission line losses (TM_l), based on a 450 kV, 2222 A transmission line with a resistance of 16 Ω/pole, is:

$$TM_l = (WTLC + O\&M + TMLC)(0.012 + 0.079 \times CF). \quad (9)$$

The levelized cost of energy (COE) delivered to the load center is then:

$$COE = WFLC + TMLC + TM_l. \quad (10)$$

The cost of electricity as a function of transmission line (system) capacity factor and the number of wind turbines in the wind farm is shown in Figure 2. Note that the busbar cost of electricity initially increases slowly as the capacity factor increases: a 36 percent increase in capacity factor can be obtained for a 10 percent increase in the busbar cost of electricity. That is to say that high capacity factors are obtainable from an oversized wind farm at a moderate increase in busbar price. The number of wind turbines in an oversized wind farm is, however, substantially greater than in the baseline case: an oversized wind farm with a 62 percent system capacity factor system has 2.15 times as many wind turbines as the baseline case.

The cost of delivered electricity is \$0.0574/kWh for the baseline case, with

transmission about 48 percent of total cost. As the number of turbines in the wind farm increases, the transmission line is better utilized (system capacity factor increases) and transmission costs decrease. The decrease in transmission cost is initially more rapid than the increase in the busbar cost of energy, so that the delivered cost of electricity decreases. Ultimately, when the decrease in transmission cost cannot compensate for the increase in busbar cost of energy, the cost of delivered electricity begins to increase. For the parameters chosen for this study, a system capacity factor of 70 percent can be obtained for an increase in delivered cost of electricity of only 6 percent, to \$0.061/kWh, compared to the baseline case. It is of some interest to note that the average capacity factor of a nuclear power plant in the U.S. is about 70 percent, and that an intermittent energy source can begin to approximate this performance.

It should be emphasized that the cost of delivered energy is a strong function of the conservative assumptions of transmission costs which could be about one-half what we have assumed (\$800 million) if the transmission line only costs are as low as those quoted by Long (1987). In this case, the cost of delivered electricity would be \$0.0543/kWh at a 70 percent system capacity factor, making wind generated electricity extremely attractive relative to other alternatives.

As the number of wind turbines is increased, the amount of power that cannot be transmitted due to the fixed capacity of the transmission line increases slowly at first, and then quite rapidly, until at a capacity factor of 78 percent, more power is being spilled than transmitted (Figure 3). This spilled power is available locally, for example to charge a compressed air energy storage system, at the O&M cost of \$0.005/kWh, and can be used to increase the system capacity factor even further.

ADDING STORAGE

Compressed Air Energy Storage

Adding additional wind turbines to the baseline wind farm is initially the most economical method of increasing the system capacity factor. However, as the system capacity factor increases above 60 percent, this becomes less true since the marginal cost of the additional capacity increases quite rapidly (see Figure 4). At some point it becomes economically attractive to add storage, rather than additional wind turbines, to enhance the system capacity factor.

There are several possible candidates for the proposed storage system: flywheels, batteries, superconducting magnetic energy storage systems, pumped hydro and CAES (Hay, 1993). The first three can be rejected on the basis of cost and/or technical immaturity. Above-ground pumped hydro is an economically attractive option, but must be rejected because there are few if any sites on the Great Plains; underground pumped storage is projected to cost \$1500/kW, far too costly for this application.

A compressed air energy storage system (CAES) is, however, ideally suited for this operation. It is a proven technology with a low capital cost. Geological conditions in western Kansas are also favorable since the salt deposits in the area provide an excellent location for the compressed air storage volume; supplies of natural gas in the area are adequate. A CAES system (Schainker et al., 1993) consists of a compressor, a turboexpander, a motor/ generator, and an underground storage volume such as a solution-mined cavern constructed in a salt dome or salt bed, a porous rock formation such as a depleted gas reservoir, or a hard rock cavern or abandoned mine. To charge the reservoir, a clutch engages the motor/generator to the compressor; the motor uses power that would otherwise be spilled by the wind farm to drive the compressor and fill the cavern with air to a pressure of about 1100 psig. When power is needed at times of low wind farm output, the motor/generator is disengaged from the compressor and engaged to the turboexpander for power generation. Air from the reservoir is preheated in a recuperator (heated by the turboexpander exhaust) and burned in the turboexpander

with distillate oil or natural gas to generate electricity. In contrast to other storage technologies, the electrical output of a CAES system is greater than the electrical input because extra power is provided by natural gas combustion in the turboexpander.

The levelized cost of the CAES system (CSLC) (including plant and storage capital cost, fuel and electricity, and operation and maintenance costs) is given by:

The installed plant capital cost (PCC) is assumed to be \$560/kW; storage system capital costs (SCC) are \$3/kWh_s (Schainker et al., 1993). The storage time h_s is the number of hours the CAES plant can run at full discharge power, CCR = 0.107, appropriate for a 25 year plant life (EPRI TAG 1989), and CF_s is the CAES system capacity factor. The cost of fuel is given by the heat rate, HR, 4100 Btu/kWh, times the fuel cost (FC) assumed to be a constant cost of \$4.1/mmBtu (EIA,1994); the marginal cost of electricity (MCOE) used to charge the storage volume is \$0.005/kWh and the electricity input-output ratio (the energy ratio, ER) is 0.67. Fixed and variable operation and maintenance costs, O&M_s, are assumed to be \$1.2/kW-yr, and \$0.0015/kWh, respectively.

The cost of electricity is (including CSLC in the computation of TM₁):

$$\text{COE} = \text{WFLC} \cdot \beta + \text{CSLC} \cdot (1-\beta) + \text{TMLC} + \text{TM}_1, \quad (12)$$

where β is the fraction of average power supplied by the wind farm to the transmission line and $(1-\beta)$ is the fraction of power supplied by the CAES system.

The capacity factor of the CAES system is estimated using an easily calculated parameter, the fraction of time that energy is being spilled from the oversized wind farm. If CF_s is taken to be 50 percent of this fraction, it implies that about 33 percent ($0.5 \cdot 0.67$)

of the spilled power is captured, a very conservative assumption. For the wind regime assumed here, CF_s is 0.15 with 15,100 wind turbines, 0.21 with 19,100 turbines and 0.28 with 27,100 wind turbines (see Figure 5).

A comparison of the marginal cost of wind turbines in an oversized wind farm with the cost of energy from a CAES system is shown in Figure 4, and demonstrate that above a system capacity factor of about 60 percent, the use of CAES becomes increasingly attractive.

System costs and capacity factors for wind-transmission and wind-CAES-transmission systems are compared in Figure 5. Very high capacity factors, not attainable with a wind only system (see Figure 2), are economically feasible if a CAES system is used to store power that would otherwise be lost to the system for transmission during lower wind velocity periods. The levelized cost of delivered electricity for a wind-CAES-transmission system at a capacity factor of 90 percent is \$0.06/kWh, which is about 4 percent greater than the cost (\$0.0574/kWh) for the baseline system at a capacity factor of 36 percent. The number of wind turbines and the maximum output of the oversized wind farm at a system capacity factor of 90 percent is a factor of three greater than for the baseline case. Intermediate system capacity factors are obtainable with wind alone, so that construction of a high capacity factor system can be done in stages over several years using proven, modular technology. Thus, high capacity factor wind farms and wind energy baseload systems are both economically and technically feasible for the wind regime of the Great Plains.

Land requirements for large wind farms are modest compared to the available windy land in western Kansas. An array of 27,100 wind turbines with a 10Dx5D spacing would cover an area of 775 km² (17.3 mi x 17.3 mi); Elliott (1991) estimates that 33,000 km² of wind class 4 land (wind power density of 450 W/m² at 50 m elevation) are available in Kansas, given moderate land use restrictions. This is an area of low population density so that visual impact should not be an issue; large wind farms are compatible with current

land use, which is wheat farming and ranching.

DISCUSSION AND CONCLUSIONS

The somewhat surprising and counter-intuitive result that wind-transmission systems can have a capacity factor of over 60 percent without an economic penalty and without storage is a consequence of the current development and design philosophy of wind turbines, which is to minimize the busbar cost of electricity with no consideration given to the wind turbine capacity factor. This is a perfectly reasonable approach for present day systems, which cover only a small fraction of utility demand and exploit resources close to demand centers. In the future, as wind generated electricity supplies a much more significant portion of total demand and more distant resources are utilized, system constraints must be taken into account, and the delivered, not busbar, cost of electricity must be minimized.

The costs assumed for different subsystems are believed to be relatively conservative. As noted, transmission line costs should be substantially below those used, significantly reducing the cost of delivered electricity. For a system in which transmission is unnecessary, the cost of delivered electricity would be about \$0.045/kWh at 90 percent system capacity factor (see Figure 5), which is very competitive with other technologies (see footnote 7).

Wind turbine installed capital costs may drop below those assumed here (see footnote 8) given the relative simplicity of these machines and the reduction in per unit cost to be expected with large scale serial production. Wind turbine O&M costs should certainly drop below those now encountered given advances in materials and design, and especially with the elimination of the transmission, which is a maintenance-intensive component.

The assumed cost of the CAES system is based on extensive studies done by the

Electric Power Research Institute (EPRI) (Schainker, 1993), and is significantly above that reported for the 110 MW, 10 hour storage capacity CAES system recently installed at Macintosh, Alabama (Jenkins, 1991). Natural gas (\$4.1/mmBtu) accounts for about 40 percent of the cost of energy from a CAES system, about equal to the levelized annualized cost of capital (the first term in Eq. 11). At a system capacity factor of 90 percent (see Figure 5), the cost of electricity from the CAES system accounts for less than 20 percent of the cost of delivered electricity (see footnote 8). Thus, even a 30 percent increase in CAES plant capital cost would result in less than a 5 percent increase in the cost of delivered electricity in this example.

From the above discussion, the following conclusions can be drawn:

- Wind generated electricity can be transformed fundamentally from an intermittent to a high capacity factor or a baseload power supply.
- Wind farms with compressed air energy storage systems with capacity factors greater than 90 percent (wind energy baseload systems) are economically attractive and technically feasible in the wind regime of the Great Plains.
- If transmission costs are included, the delivered cost of electricity can be lower at higher system capacity factor .
- Use of compressed air energy storage systems reduces the cost of delivered electricity for very high capacity factor systems where transmission costs are significant.

This approach is ideally suited to the industrial scale development of the wind resources of the Great Plains. It is based on existing technologies whose cost and performance is well documented. In addition, it would make optimum use of transmission systems, which are expensive to build and difficult to site.

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Figure Captions

Figure 1. Wind turbine capacity factor vs. Weibull k parameter for a wind regime with $P_w=440 \text{ W/m}^2$.

Figure 2. Cost of electricity by component vs. system capacity factor and number of wind farms for baseline and oversized wind farms ($P_w=440 \text{ W/m}^2$, $k=3$ wind regime).

Figure 3. Power transmitted, power lost vs. system capacity factor.

Figure 4. Marginal cost of wind energy for oversized wind farms and CAES cost of energy vs. system capacity factor ($P_w=440 \text{ W/m}^2$, $k=3$ wind regime).

Figure 5. Cost of electricity by component vs. system capacity factor and number of wind turbines for baseline and oversized wind farms, and for oversized wind farms with storage ($P_w=440 \text{ W/m}^2$, $k=3$ wind regime).