High-Capacity Factor Wind Energy Systems

Alfred J. Cavallo (1)
Center for Energy and
Environmental Studies,
Princeton University,
Princeton, NJ 08544

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(2). 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 base load 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 co lid. for example, replace the nuclear power plants at Diablo Canyon, CA. (2 x 1100 MWe. 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

---

(1)Currently at the U.S. Department of Energy. Environmental Measurements Laboratory. 376 Hudson Street. Sew York. NY 10014-3621.

Contributed by the Solar Energy Division of THE AMERICA.NSOCIETY OF MECHANICALENGINEERS for publication in the ASME JOURNAL OF SOLAR ENERGY ENGINEERING. Manuscript received by the ASME Solar Energy Division. Apr. 1994; final revision. Sept. 1994. Associate Technical Editor: P. S. Veers.

(2)Typical capacity factors (the ratio of average power output to maximum power output) for large base load coal-fired power plants are *75~80* percent: the average capacity factor for nuclear power plants in the U.S. is about 70 percent (Northwest Power and Conservation Plan. 1991: EIA, 1994). A base load power plant is not dispatchable and is. ideally. able to deliver itS full-rated power 100 percent of the time. A reduction in output is due to either a forced outage. that is an accident or equipment breakdown. or a scheduled outage. that is time out of service for repair and maintenance. For an intermittent power source such as a wind farm, the reduction in capacity factor can be viewed as due entirely to forced outages: as with other base load systems. a wind energy system is a must-run installation. and its output cannot be dispatched. or controlled, bv a utility.

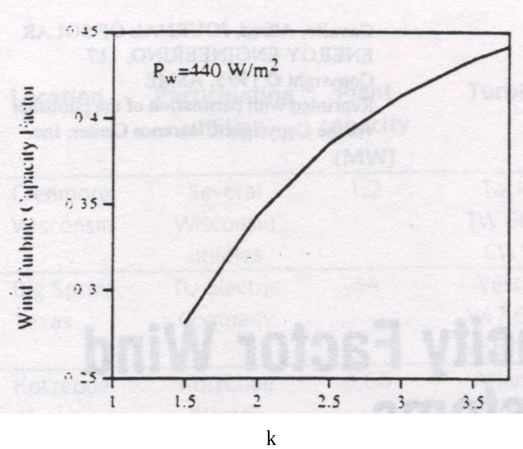

Fig. 1 Wind turbine capacity factor versus Wiebull k parameter for a wind regime with Pw = 440 W/m2

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):

$$f(v) = \frac{k}{c}\cdot\left(\frac{v}{c}\right)^{k-1}\exp-\left(\frac{v}{c}\right)^{k}. \qquad (1)$$

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 (Pout) of a wind turbine as a function of wind velocity is written as

$$P_{\text{out}} = P_{\max}\cdot g(v). \qquad (2)$$

The average power output (Pavg) of a wind turbine can be written as

$$P_{\text{avg}} = P_{\max}\int f(v)\cdot g(v)\cdot dv. \qquad (3)$$

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 ma.ximum turbine output and is defined as the wind turbine capacity factor (WTCF). In Fig. 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/m2, which is typical of that found over large areas of the Great Plains. The published characteristics of the Vestas V27-225 wind turbine[3] (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 varietv 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 GWavg: 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/m2. The high yearly average indicates an economically viable resource, while the high summer average indicates that system output will be high in the summer,when utility demand is greatest. (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 *Pw*.= 440 W/m2 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(4) 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 m (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. Quebec, and Boston, MA (Reason, 1990) as well as on information given bv Long (1987). The agreement to build the HQ (Hydro Quebec) 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: W'atkins (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 berore 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 U.S. while in Quebec the right of way had to be acquired and extensive road construction was necessary. According to project engineers(5), the transmission line cost about $0.62 million per krn ($1 million per mile) both in the U.S. and in Quebec. The cost of the converter stations (345 kV AC to 450 kV DC), filters and circuit breakers in the US was S320 million. Converter losses are 0,6 percent per sta-

---

(1)The power output curve of the V'27-225 as a function of wind velocity : (m 8I can. *be* written aS *P(kw)* = O. t;:::;: 3. ~.~ :5: *P* (kW) = 22591: (n5E - 2' - 15.o9~£ - 2 . ~.)- (3.3~8£ - :. t;=) - tO.916£ - " - \ I.~n: ~ - 3 · ;~) - (0.9'1-£ - ~. *L*") - \2.36£ - n . ~.h)l.

(4)Most wind turbinemanufacturers now offer 40-m towers. and a few already offer 50-m toweers. The higher Weibull *k* values at higher elevations make tall towers more economical than was previously believed.

(5)Costs, including transmissson line O & M costs. were obtained from discussions with Bradley D. Railing. station engineer for New England Electric Corporation. Jacque Allaire. or' Hydro Quebec. Mlontreal. and MichaeI P. Bahrman. ABB Power Systems. Ayer. M.A.

tion:line resistanceis 12 ohms 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 seven 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 substantiallv greater than the HVDC line cost ($19*-229/kV-km) cited by Long (1987). However. the HVAC transmission line cost of S560/kV-km quoted by Watkins (1991) agrees well with that given by Long ($516-607/kV-km for HVAC single-circuit transmission lines). It mav 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.

HYDC converter costS of about $110/kW are also quoted by Long (1987), and are significantly less than the $160/kW for the HQ svstem. 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 fann 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

$$N \cdot P_{\max} = 2000\ MW. \tag{4}$$

The capacity factor of this system is thus the capacity factor of the wind farn. which is the wind turbine capacity factor reduced bv 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 $P_w = 440\ W/m^2$ and a $k = 2$ wind frequency regime. is 34.3 percent. If the average arrav[6] 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 (1OD x 5D). 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 ($P_w = 440\ W/m^2$. $k = 3$). 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 fann. 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):

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

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( )[7]: system capacity factor increases from 0.36 to 0.41 percent(8). As the number of wind turbines is increased further. Pmax begins to decrease: with 12600 wind turbines. *Pmax* 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 *Pavg* 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.

Finallv. storage can be added to the svstem to utilize the energy that wo~ld normally be lost when the output of the oversized wind farm exceeds the capacity of the transmission line.

Cost of Electricitv. 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

$$\mathrm{WTLC} = \frac{\mathrm{ICC} \cdot \mathrm{CCR} \cdot N}{N \cdot P_{\mathrm{avg}} \cdot 8766 \cdot (1 - A)}. \tag{6}$$

Here N is the number of wind turbines in the wind fann. ICC is the installed capital cost. assumed to be $700/kW

---

(6)Array losses and other losses for wind farms in the Great Plains are expected to be 10 to 15 percent. much lower than is found in California. This is due to the thicker boundary layer. which allows for a much more rapid wake replenishment. Losses caused by blade soiling are expected to be much lower due to the development of airfoils that are less sensitive to soiling. A recent evaluation of the wmd electric potential of the Great PlaIns (Brower. 1993) assumed array and other losses reduced wind farm output by' ten percent for a 50 MW'wind farm with an 8D x 5D machine spacig. This is based on the recent Kenetech proposal for a wind farm \now installed and in operaton) on Buffalo Ridge. MN. Availability of 100 percent is also assumed. This is reasonable for the oversized wind farms. since by definition some of the wind turbines wIll often be forced to shut down due to limitations on the transmission line capaciry.

Array losses are a function of wind speed. wind frequency distribution. and wind turbine spacing. For a uniform wind turbine spacing. array iosses are negligible at hIghwind velocities where wind turbine efficiency is low. but the wind turbine is generating maximum power. At lowerwind speeds. where wind turbine efficiency is high. and the energy extracted from and the velocitvreductionof the wind stream are a maximum array losses are a maximum.

'To compute the capaciry factor of the oversized wind farm here. the small amount of energy lost at high wind velocities where array losses are low and transmission iine capacity might be exceeded is ignored. This can be justified as follows: The number of wind turbines in the wind farm and maximum power output of the wind farm increases by 12 percenL from $N = 8900$ and $P_{max} = 2000$ MW to $N = 10100$ and $P_{max} = 2240$ MW, in this case. If arrav and other losses were constant as a function of ind velociry. both the maximum power output of the now oversized wind farm and the average power output (or energy) per wind turbine. would decrease by 12 percent. and the additional wind turbines would simply make up for array and other losses in the baseline wind (arm. Howeever. as indicated above. the actual situation is more complex. since losses are not independent of turbine output (or wind velocity). Array losses. which are the moSt important, are a function of wind velociry: resistive and transformcr losses are low when the wind farm output is low. and are a maximum when the power output is maximum. For the wind regime and turbine output characteristics assumed here. less than eIght percent of the energy is obtained from winds above 14 m/s. where the wInd turbine power output is at itS maximum of 225 kW. In other words. in this wind regime. the wind turbine produces power at its maximum output about 3.2 percent of the time. Thus. the approximation that losses are constant (that is the variation of the losses with velociry can be neglected) is a reasonably good one. The wind turbine capacity factor may also be enhanced by taking ad\antage of site specific characteristics.

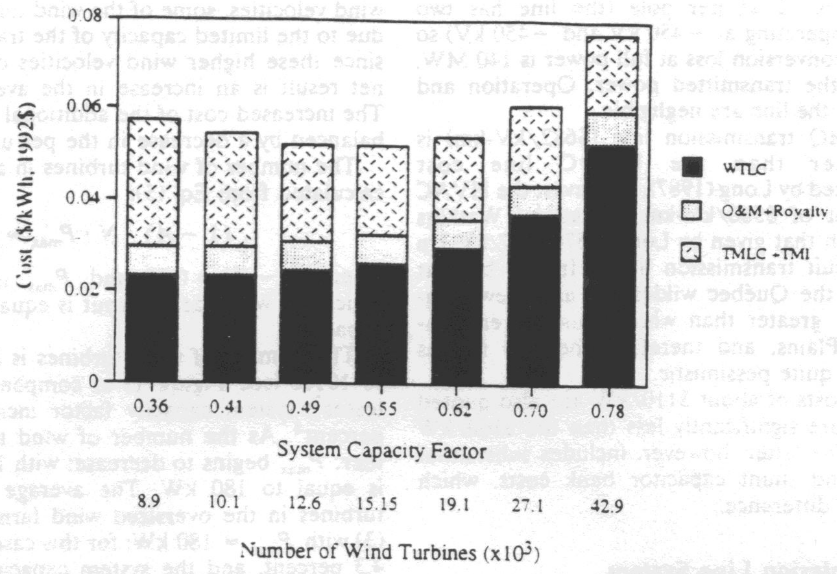

Fig. 2 Cost of electricity by component versus system capacity factor and number of wind turbines for baseline and oversized wind farms (P_w = 440 W/ m², k = 3 wind regime)

(1992$) (Miller. 1994)(9) 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/m2.

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 four 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

$$\mathrm{WFLC} = \mathrm{WTLC}\ /\mathrm{O}\ \&\ \mathrm{M} + \mathrm{Royalty}. \tag{7}$$

The transmission line levelized cost (TMLC) is

$$\mathrm{TMLC} = \frac{\mathrm{TMCC} \cdot \mathrm{CCR}}{\mathrm{CF} \cdot 2 \times 10^6 \cdot 8766}. \tag{8}$$

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 (TM1)' based on a 450 kV. 2222 *A* transmission line with a resistance of 16 ohm/pole, is

$$\mathrm{TM1} = (\mathrm{WTLC} + \mathrm{O}\ \&\ \mathrm{M} + \mathrm{TLMC})(0.012 + 0.079 \times \mathrm{CF}). \tag{9}$$

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

$$\mathrm{COE} = \mathrm{WFLC} + \mathrm{TMLC} + \mathrm{TM1}. \tag{10}$$

The cost of electricitv as a function of transmission line (system) capacity factor and the number of wind turbines in the wind farm is shown in Fig. 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 six 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 onlv costs are

---

''Kenetech is now signing power purchase agreements with utilities based on installed capital costs of $840/kW: costs are expected to decrease by at least 25 percent (to $630/kW) by the year 2010. The installed wind turbine capital cost is conservatively assumed to be $700/kW: the wind turbine assumed in this sludv has the power output charactenstics of the Vestas V27-225 with a hub height of 50 m. an Installed capital cost of $700/kW and is manufactured by a large industrial enterprise that may or may nOt be one of the organizations cited above.

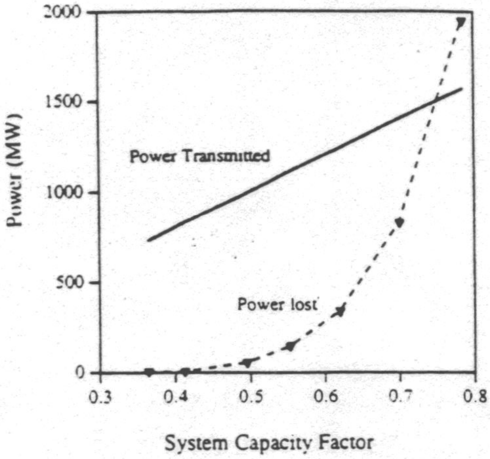

Fig. 3 Power transmitted, power lost versus system capacity factor

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 (Fig. 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 about 60 percent. this becomes less true since the marginal cost of the additional capacity increases quite rapidly (see Fig. 4). At some point it becomes economically attractive to add storage[10]. 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 an'll 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.

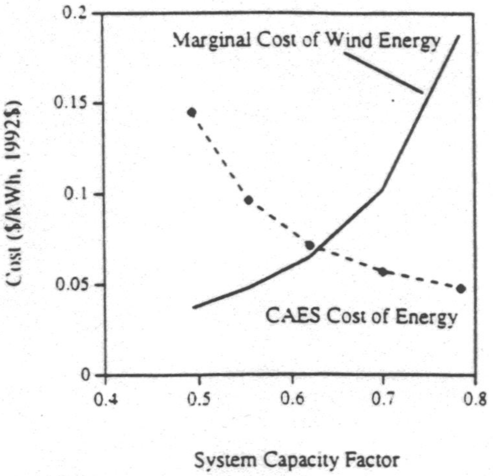

Fig. 4 Marginal cost of wind energy for oversized wind farms and CAES cost of energy versus system capacity factor (P_w = 440 W/m^2, k = 3 wind regime)

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

$$\mathrm{CSLC} = \left(\frac{(\mathrm{PCC} + \mathrm{SCC} \cdot h_s) \cdot \mathrm{CCR}}{\mathrm{CF}_s \cdot 8766} + (\mathrm{HR} \cdot \mathrm{FC}) + \mathrm{MCOE} \cdot \mathrm{ER} + (\mathrm{O\&M})_s \right). \quad (11)$$

The installed plant capital cost (PCC) is assumed to be $560/kW; storage system capital costs (SCC) are $3/kWh, (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 $O.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.

---

[10] Another possibility is to use high efficiency aeroderivative gas turbines to back up the wind farm output and increase the transmission line capacity factor. The General Electric LM6000, which has a heat rate of 9500 Btu/kWh (0.75 full load) and an installed capital cost of $440/kW (Wen, 1991) could produce electricity for about $0.06/kWh, compared to about $0.045/kWh with the CAES system (CF = 0.4 for both systems, natural gas at $4.1/mmBtu). Therefore, on simple economic grounds, this does not appear to be a viable alternative. There are also regulatory and operational barriers to using gas turbines to back up wind farms. For example, the Federal Energy Regulatory Commission (FERC) does not allow natural gas to be used to back up the output of a wind farm (Jourolman, 1992); from an operations perspective, a utility would be more likely to install gas turbines close to a demand center, where their output might be dispatchable.

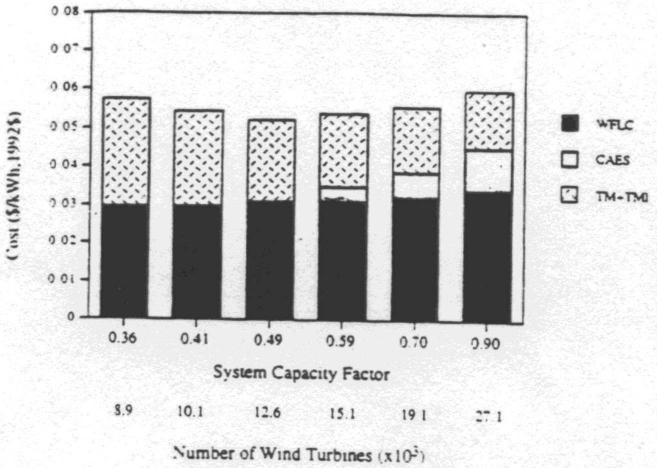

Fig. 5 Cost of electricity by component versus system capacity factor and number of wind turbines for baseline and oversized wind farms, and for oversized wind farms with storage (P_w = 440 W/m^2, k = 3 wind regime)

The cost of electricity is (including CSLC in the computation of TM_1):

$$COE = WFLC \cdot \beta + CSLC \cdot (1 - \beta) + TMLC - TM_1 . \quad (12)$$

where 13 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 spiIled from the oversized wind farm: if CFs is taken to be 50 percent of this fraction. For the wind regime assumed here. *CFs* is 0.15 with 15.100 wind turbines. 0.21 with 19,100 turbines and 0.28 with 27.100 wind turbines (see Fig. 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 Fig. 4. and demonstrates that above a system capacity factor of about 60 percent, the use of CAES becomes increasingly attractive (11).

System costs and capacity factors for wind-transmission and wind-CAES-transmission systems are compared in Fig. 5. Very high-capacity factors, not attainable with a wind only system (see Fig. 21, are economicallv 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 electricitv for a wind-CAES-transmission system at a capacity factor of 90 percent is $0.06 kWh, which is about four 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 base load svstems are both economically and technicalIy 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 Vestas V27-225 wind turbines with a 10D x 5D 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 (12). 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, svstem 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 substantiaIly below those used. significantly reducing the cost of delivered electricity. For a system in which transmission is unnecessarv, the cost of delivered electricity would be about $0,045/kWh at 90 percent system capacity factor (see Fig. 5), which is very competitive with other technologies (see footnote 10).

Wind turbine installed capital costs may drop below those assumed here (see footnote 9) 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. ten-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 Fig. 5). the cost of electricity from the CAES system accounts for less than 20 percent ofthe cost of delivered electricity. Thus, even a 30 percent increase in CAES plant capital cost would result in less than a ffiye 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 base load power supply,

> Wind farms with compressed air energy storage systems with capacity factors greater than 90 percent (wind energy

---

[11] A more detailed simulation of the oversized wind farm-CAES-transmission system using computer-generated hourly wind data yields much higher CAES capacity factors and lower cost of delivered energy.

[12] Moderate land use restrictions exclude from development all environmentally sensitive and urban lands. 50 percent of forest lands. 30 percent of farm lands. and 10 percent of range lands: large tracts of wind class 4 land are also available in western Oklahoma and northern Texas.

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 perfonnance is well documented. In addition. it would make optimum use of transmission systems. which are expensive to build and difficult to site.

Acknowledgments

General discussions with Robert Williams and with Gregory Terzian on utility-wind fann integration issues have been most helpful in clarifying the ideas presented here. Extensive discussions with Eugene Ciancanelli and Carl Nelson on underground CAES reservoirs and with Eric Swensen on the above ground portion of the CAES plant were most valuable. The DOE Tall Tower Data was generously provided by Dennis Elliott; Donna Riley's help with the analysis of this data was invaluable. The financial support of The Energy Foundation and of the W. Alton Jones Foundation is most appreciated.

References

Brower. M1.. Tennis. MI.. Denzler. Eo. and Kaplan. M.. 1993. "Powering the Mlidwest. Union of Concerned Scientists. Cambridge. MA.

Cavallo. A.. 1992. "The Economics of the Exploitation of Wind Generated Electricity in the Great Plains.' *Proceedings of W'"dpower* 92. American Wind Energy Association. Washington. DC

Cavallo. A.. i993. "Wind Energy: Current Status. Future Prospects. *SCience and Global Secunry.* Vol. 4. pp. 65-109.

Cavallo. A.. 1994. ¨ High Capacity Factor Wind Turbine-Transmission Systems.' *Proceed"'gs of the 13th Wind Energy S,mposium. Energy Sources Technology' Conference.* New Orleans. Solar Energy Division. Vol. 15. Pp. *S7-94.* .AS.W1E.New York.

Elliott. D. L.. Holladay. C G.. Barchet. W. R.. Foote. H. P.. and Sandusky.: W. F.. 1987. "Wind Energy Resource .Atlas of the U'nitcd States. - Pacific Northwest Laboratories. ¯ Richland. WA. DOE/CH 10094-4.

Elliott. D. L.. Wendell. L. L.. and Gower. G. L.. 1991. "An Assessment of the Available Windv Land .Area and Wind Energy Potential in the Contiguous United States.' PNL-7789. Pacific Northwest Laboratories, Richland_ WA.

Elliott, D. T.. 1994. private communication. Pacific Northwest Laboratories. Richland. WA. Jan.

EIA (Energy Information Agency). 1994. "Annual Energy Outlook 1994.- DOE/EIA-0383(94)." U.S. Department of Energy. Washington, DC

EPRI (Electric Power Research Institute). 1989. Technical Assessment Guide. Vol. 1. Electricity Supply. Palo Alto. CA. EPRI Report P-6587-L.

Enercon. 1993. Dreekamp 5. D-2960. Aurich. Germany.

Friis. P.. and Mogens. H.. 1993. "Commercial and Experimental Wind Power in E1sam Utility Area. Denmark,- *Proceedings. Windpower* 93. San Francisco. July 12-16. American Wind Energy Association. Washington. DC.

Grubb. *M.*. 1991. "The Value of Variable Sources on Power Systems." *lEE Proceedings* C. Yol. 138. p. 2.

Grubb. M.. and Meyer. H.. 1992, '"Wind Energy: Resources. Systems and Regional Strategies." *Renewable Energy: Sources for Fuels and Electricity.* T. B. Johannson. H. Kelly. A. K. N. Reddy. and R. Williams. eds.. Island Press. Washington. DC

Harrison. L.. 1993. "Juggling With New Balls_- *Windpower Monthly.* Vol. 9. pp. 33-36.

Haslett. 1.. and Diesendorf. M.. 1981. "The Capacity Credit of Wind Power: A Theoretical Analysis," *Solar Energy.* Vol. 26. pp. 391-401.

Jenkins. A.. 1991. Technology Characterization. Final Report. November 1991. California Energy Commission, Sacramento. CA.

Johnson, G.. 1985. "Wind Energy Systems." Prentice-Hall. Englewood Cliffs. NJ.

Jourolman. L., 1992. "PURPA Handbook for Independent EleCtric Power Producers, American Wind Energy Association. Washington. DC.

Long. W.. 1987. "Comparison of Cost and BenefitS for AC and DC Transmission," ORNL-6204. Oak Ridge National Laboratory. Oak Ridge, TN.

Lvnette. R.. 1989. "Assessment of Wind Power Station Performance and' Reliability, EPRI Report GS-6256. Electric Power Research Institute. Box 50490. Palo Alto. CA.

Miller. E.. 1993. U.S. Windpower (Kenetech) letter to Lloyd Wright. U.S. EPA. Mav 27.

Northwest Power and Conservation Plan. 1991. Volume II, Part 1. Northwest Power Planning Council. 851 S.W. Sixth Ave.. Portland, Oregon 97204.

Reason. J.. 1990. "HVDC Line Brings Canadian Hydropower to New England: *Electrical War/d.* Yol. 3. pp. 27-32.

SERI (Solar Energy Research Institute. now NREL). 1990. "The Potential of Renewable Energy: An Interlaboratory White Paper' SERI/TP-260-3674. National Renewable Energy Laboratory. Golden. CO.

Schainker. R. B.. Mehta_ B.. and Pollak, R.. 1993" "Overview of CAES Technology' *Proceedings of the American Power Conference.* Chicago. Illinois Institute of Technology. Chicago. IL. pp. 992-997.

Vestas. 1993. Smed Hansens Vej 27. DK-6940. Lem_ Denmark.

Watkins. K.. 1991. "Blackfeet Area Wind Integration Study." PNUCC. One Main Place. 101 S.W. Main. Suite 810. Portland. OR.

Wen. H.. 1991. personal communication. Fossil Technology Group. Bechtel Power Corporation. Gaithersberg. MD.

Wu. C T._ eds.. 1990. "AC-DC Economics and Alternatives." *IEEE TransactiOns on Power Delivery'.* Vol. 5. pp. 1956-1969.