Optimizing Transmission from Distant Wind Farms

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Abstract

Using the actual distribution of electricity production from four wind farms in the northeastern United States whose capacity factors are 29-34%,we calculated the optimal size of the transmission line connecting the wind farms to distant customers. For a distance of 500 miles, the optimal transmission capacity is about 86 %; for a 1,000 mile separation, the optimal transmission capacity is 75 %. Building a line at full capacity would increase transmission cost almost 15 % while transmitting only about 4% more electricity to the customer. For a Western wind farm with a capacity factor of 50%, the optimal transmission line would have 89 % of the capacity of the wind farm at 500 miles and 85 % at 1,000 miles.

When two wind farms use the same central transmission line, the optimal transmission capacity varies with the correlation between the outputs of the two wind farms. For a correlation of -1,0, the optimal capacity is 1.00, while for a correlation of 1.0, the optimal capacity is slightly more than 75%. The correlation between the outputs of wind farms depends, among other factors, on the distance between wind farms. We estimate that relationship and use it to optimize the location of a second wind farm. The cost of the transmission line between the two farms largely offsets the benefit of a lower output correlation, since the profit maximizing distance between the two wind farms has little effect on the cost of delivered electricity. Somewhat surprisingly, adding a second wind farm does little to lower the transmission cost of delivering power to the customer. The cost saving from bundling 2 wind farms largely depend on the distance between the wind farms.

Finally, we model a system where the owner is penalized \$200/MWh whenever delivered output falls below 400 MW. In this case, the penalty means that the second wind farm increases profit and should be located further from the first to maximize profit. Bundling wind farms with low correlation can smooth output distribution and increase reliability of the delivered output. However, the developer needs to trade off between the increase in transmission cost and reliability of the delivered output.

The cost of delivered electricity varies little whether there is one or two wind farms on the transmission line. Using current estimates of the cost of a wind turbine and the cost of a transmission line, we estimate that the cost of delivered power from a wind farm with about 33% capacity that is locate 1,000 miles from the customer will be about $150/MWh with almost 2/3 of the cost due to transmission. This cost does not include measures to solve the moment to moment variability of wind turbine output or the intermittency of output. If the latter cost were imposed for power output less than 40% of wind farm capacity, profit of the wind farm decreases significantly especially for the pair of wind farms with high output correlation.

1. Data and Assumptions

1. Wind data

Hourly wind data covering January-June for four U.S. wind farms are used. The data were normalized such that the maximum output (equaling the nameplate capacity) was equal to 1. Descriptive statistics and output correlation & distance between farms are presented in the tables below.

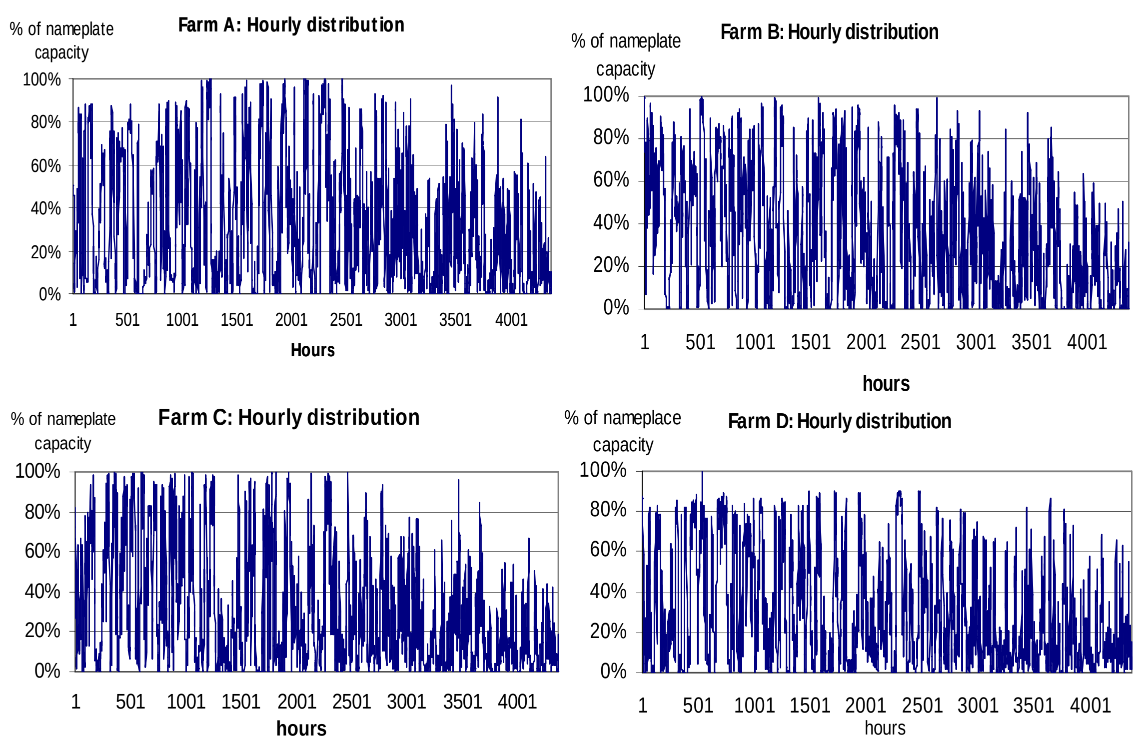


Figure 1: Hourly distribution of wind power

Table1: Descriptive statistics of the wind farm output

Wind farm	Capacity factor (%)	Variance
A	32.73	0.0840
B	34.73	0.0871
C	29.92	0.0821
D	29.77	0.0738

Table 2: Output correlation between farms

	A	C	B	D
A	1.00	0.69	0.77	0.35
C	19	1.00	0.71	0.36
B	56	63	1.00	0.46
D	219	200	250	1.00

Note: Distance between farms (miles) shown in bottom half of matrix

2. Financial variables

The discount rate in this model is 10.4% (20% equity at 20% and 80% debt at 8%). The lifetimes of the transmission line and wind turbine are 40 and 20 years respectively. For simplicity we assume that construction is instantaneous for both transmission and turbines.

3. Transmission cost function and data

Electricity transmission has important economies of scale over the relevant range (Weiss and Spiewak (1999)). The transmission line cost is *C(q)* per mile, where *q* is the capacity of the line. *C(q)* is increasing and concave, $C'(q) \geq 0$ and $C''(q) \leq 0$

To estimate the transmission cost function we used DOE (2002) data from a 1995 study. The data are adjusted to reflect the current cost of transmission construction. The transmission line cost function is estimated as a log-linear function of transmission capacity (MW). As expected, this function displays economies of scale. Using ordinary least square (OLS) the estimated transmission line cost, as a function of capacity is;

$$\text{Transmission line cost per mile } C(MW) = e^{10.959} MW^{0.5758}$$

$$(t = 36.67) \quad (t = 10.24) \quad R^2 = 0.94$$

4. Wind turbine cost

Costs of new wind turbines have risen markedly in the past few years. We use an estimate of $1,650/kW (NREL WINDS model, 2007).

5. Electricity price

The electricity price is the real hourly electricity price. Since the wind farm operator has little control over when the turbines generate electricity, we assume that she receives the average price for the year for each MWh. This assumption is in line with the current wind power purchasing status in the USA. According to Barradale (2008), about 76% of wind power capacity was purchased via a long term PPA (Power Purchasing Contract). These contracts impose the fixed price or price adjusted by inflation. In addition, although there are variations in wind patterns from year to year, these cannot be forecast with confidence and so we assume that the wind distribution (output) is the same in all years.

2. Model: One Wind Farm

The wind farm investor strives to maximize the net present value of the project. We model the choice of the transmission line capacity, given the capacity of one or more wind farms. For a project with one wind farm and one transmission line, the general form of the objective function is;

$$\underset{s}{MAX}\ \ NPV = \sum_{j=1}^{40}\sum_{i=1}^{N}\frac{p_{ji}q_{ji}(s,K)}{(1+r)^{j}} - aC(sK) - WC_1 - \frac{WC_2}{(1+r)^{20}}$$

K = the total capacity of the wind farms (MW)

s = the transmission capacity/K: $0 \le s \le 1$

a = length of the transmission line (mile)

$aC(s,K)$ = cost of a miles transmission line with capacity sK MW built in year 0

P = the average price for electricity for a year

N = 8,760 hours in a year

$q_{ji}(s,K)$ = the expected delivered wind power in year j at hour i (MWh). If $q_i > sK$, then $q_i = sK$.

r = the discount rate

WC_1 = cost of the wind turbines built in year 0

WC_2 = cost of the wind turbines built in year 20

The investor will forecast the stochastic variables in the objective function including the wind power output and hourly price in order to evaluate the NPV of the project. However, in this paper, we need to study the behavior of the optimal size of the transmission line given the set of the exogenous variable. By using randomness of the future values of the variable, we can find the optimal size of the transmission line but we cannot clearly explain the effect of the exogenous variables on the size of transmission line.

$$\underset{s}{MAX}\ \ NPV = P\sum_{i=1}^{N} q_i(s,K)\left(\sum_{j=1}^{40}\frac{1}{(1+r)^j}\right) - aC(s,K) - WC_1 - \frac{WC_2}{(1+r)^{20}}$$

Let $\sum_{j=1}^{40}\frac{1}{(1+r)^j} = \beta$, $\sum_{i=1}^{N} q_i(s,K) = Q(s,K)$ and $WC_1 + \frac{WC_2}{(1+r)^{20}} = WC$.

The above objective function can be rewritten as;

$$\underset{s}{MAX}\ \ NPV = \beta PQ(s,K) - aC(s,K) - WC$$

First order condition:

$$\frac{dNPV}{ds} = \beta P\frac{dQ(s,K)}{ds} - a\frac{dC(s,K)}{ds} = 0$$

$$\beta PQ'(s,K) = aC'(s,K)$$

From the first order condition, the firm maximizes profit when the marginal cost of adding transmission capacity, $aC'(s,K)$, is equal to the marginal benefit from additional delivered output, $\beta PQ'(s,K)$. The function $Q(s,K)$ cannot be formulated explicitly. Thus, the optimization problem is solved numerically. However, the firm will decide to invest in the wind power project only if profit is positive.

This model is optimized in 3 different scenarios

- Scenario 1: Transmission line length is 500 miles with actual wind capacity factor
- Scenario 2: Transmission line length is 1,000 miles with actual wind capacity factor
- Scenario 3: Transmission line length is 500 and 1,000 miles but wind capacity factor is adjusted to 50% by adding the same amount of power to the first 3,800 observations of the actual wind power data.

2.1 Results

The detail computation results are presented in Appendix C, Result 1 and 2. As expected, among the four wind farms, those with a higher capacity factor have a higher transmission utilization rate, lower costs, and thus higher profit.

The wind distribution also affects the optimal investment decision. The results from the adjusted capacity factor data, scenario 3, (Appendix 3, Result 3 and 4) show the effects of output distribution on transmission investment. All 4 wind farms' output data are modified to 50% capacity factor. Profit and delivered output for farm A, B and C are similar. They have almost the same transmission capacity. However, Farm D needs lower transmission capacity and has highest profit. Farm D has less output distributed in the range 0.8 – 1.0. As a result, farm D faces less trade-off between transmission capacity and loss of high level output.

If the wind turbines generated full power part of the time and no power the rest of the time, the transmission line either would not be built or it would have the same capacity as the wind farm. However, most hours turbines's output is partial, with only a few hours per year at full output. Figure 2 shows the relationship between the capacity of the transmission line and delivered wind power output. The slope of the graph represents the marginal benefit of the transmission capacity. As transmission capacity increases, marginal benefit decreases.

The finding that the optimal transmission capacity is less than the wind farm's capacity is evident in the computation results. In the second scenario, for farm A the optimal transmission capacity is around 75% of the farm's capacity, but the transmission line delivers around 96% of the wind power generated by that farm. Increasing transmission line capacity to 100% of the capacity of the wind farm will increase cost by almost 15 % but increase delivered output by only 4% .

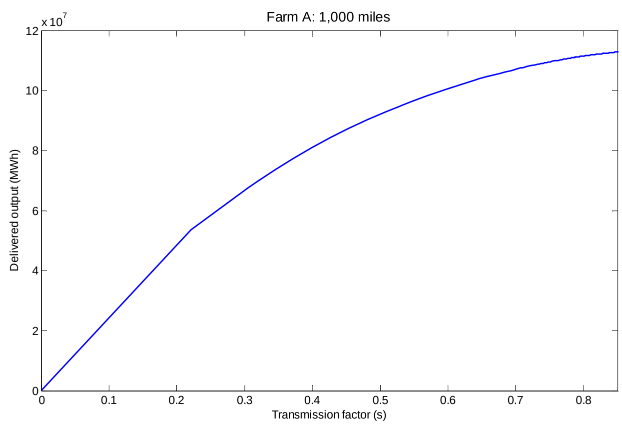


Figure 2: Transmission capacity and delivered output

Figure 3 shows the relationship between price and transmission capacity (s) in Scenario 2. For prices below $80 /MWh, the project loses money and so transmission capacity is zero. Optimal transmission capacity and delivered power rise rapidly as price goes from $85 – $200 /MWh due to economies of scale in transmission investment. The scale economies are essentially exhausted by the time a $300 price is reached; little additional transmission capacity would be added above this price.

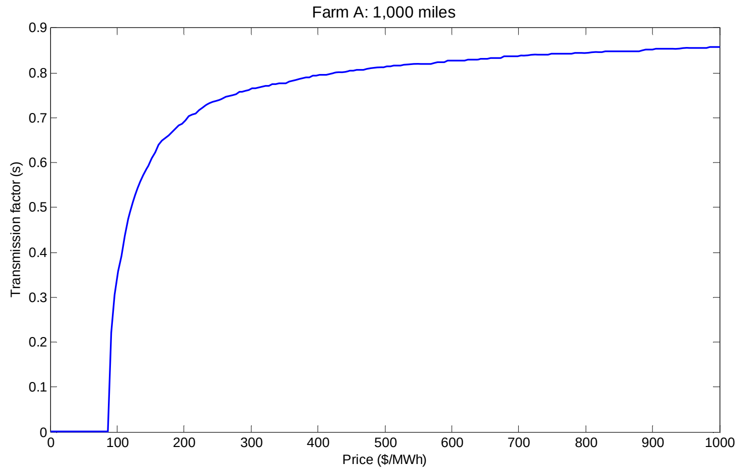


Figure 3: Price vs. transmission capacity (s)

Figure 4 shows the supply curve of farm A in scenario 2. As expected from Figure 12, there is no delivered output from the farm when price is lower than 85 $/MWh. At price below 85 $/MWh, marginal cost is greater than the marginal benefit and thus the optimal solution is to build nothing (transmission capacity = 0). Price increases justify more transmission capacity, leading to more delivered output. Supply increases steeply in the price range 85 – 200 $/MWh, and rises slowly for higher prices.

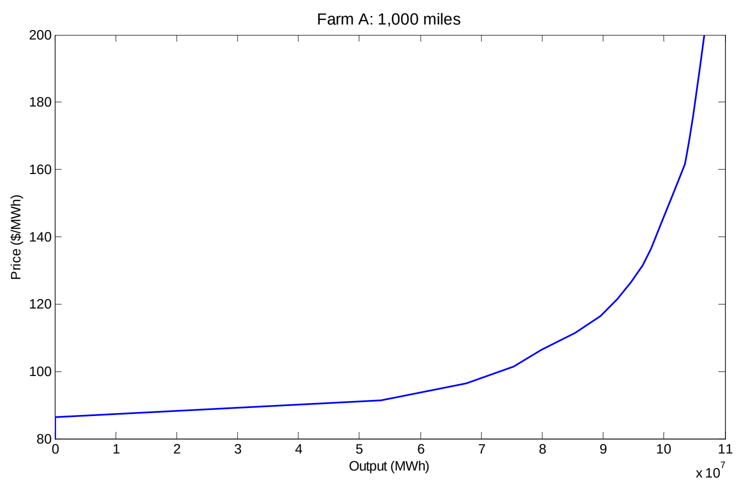


Figure 4: The supply curve

The first order conditions give a relationship between cost and price, even if the profit is negative. In figure 5, the curve shows the relationship between the market price and unit cost of the output at the profit maximizing output level. The straight line is the locus of points where unit cost equals price. The intersection between the curve and the straight line is the zero profit point (price is equal to the unit cost). The intersection marks the point of lowest unit cost. Prices to the right of the intersection lead to successively higher profit. Costs fall initially because of economies of scale in transmission and the fact that the line is loaded most heavily. As price continues to rise, transmission capacity increases but the reduced loading on the line raises unit cost. From the second scenario, total cost per unit of all 4 wind farms is from 170 - 198 $/MWh and the wind turbine cost is from 68 - 82 $/MWh. Transmission cost is around 2/3 of the total cost.

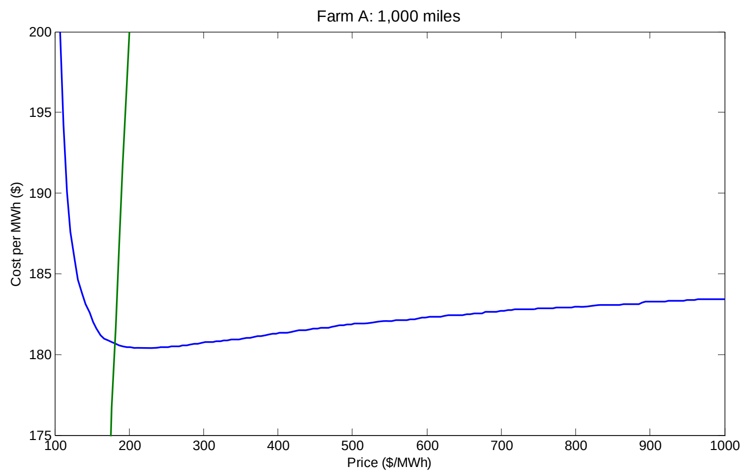


Figure 5: Price vs. unit cost at profit maximization output

Sensitivity analysis

Transmission capacity and length: Transmission cost is directly proportional to transmission length. As transmission cost increases, the optimal transmission factor (capacity of the line divided by wind farm capacity) of the line decreases for a given price, as shown in Figure 6.

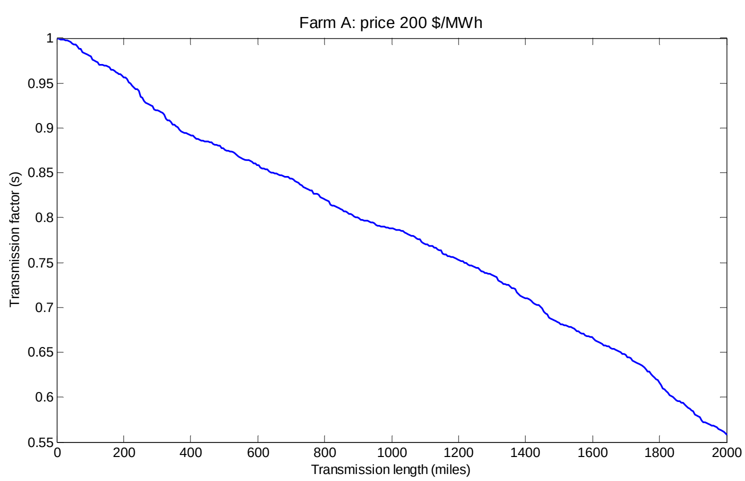


Figure 6: Optimal transmission capacity and transmission length

Transmission capacity and discount rate: Increasing the cost of capital increases the cost of the transmission line. Figure 7 shows that the optimal capacity of the line declines as the discount rate increases.

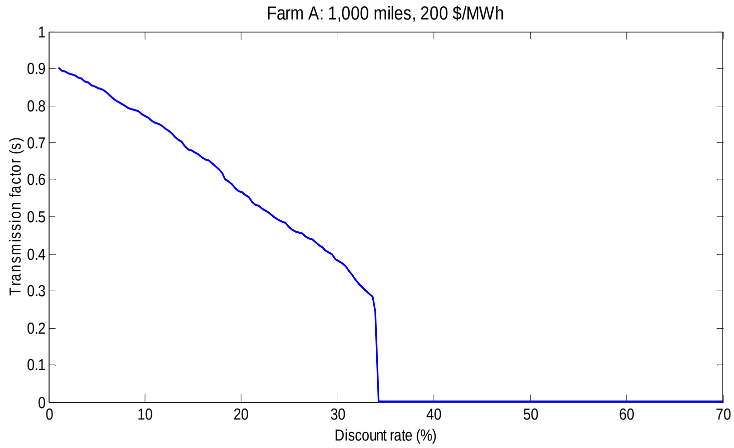


Figure 7: Optimal transmission capacity and discount rate

Profit and discount rate: Figure 8 shows the relationship between profit and discount rate. Profit steadily decreases as the discount rate increases. IRR (Internal Rate of Return) of this project is around 14% (zero NPV discount rate). The IRR is greater than the discount rate because at price equal to 200 $/MWh the wind farm makes positive profit.

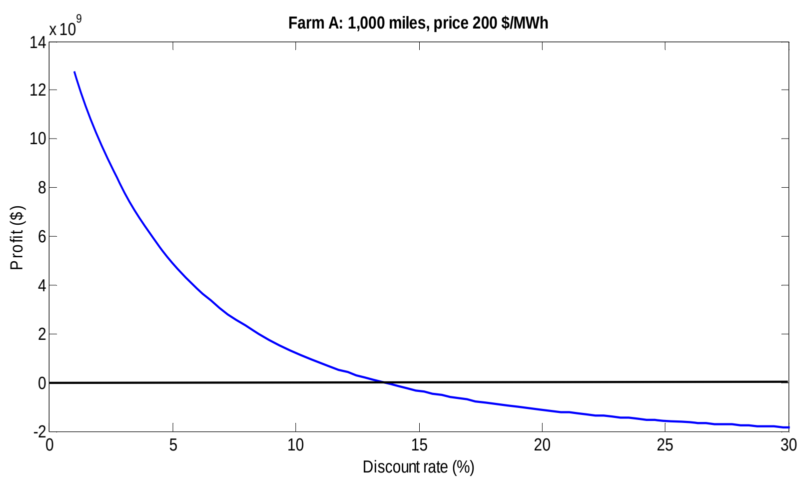


Figure 8: Profit and discount rate

3. Model with 2 wind farms

The model with 2 wind farms has one branch line connecting the second wind farm to the main transmission line and one main transmission line. Figure 9 illustrates the model.

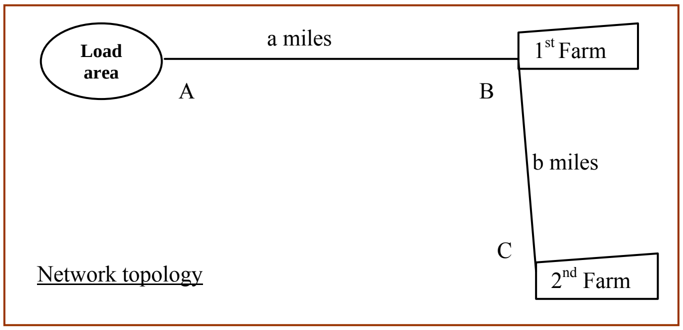


Figure 9: Simplified network topology of the model with 2 wind farms

Both wind farms are assumed to have the same capacity. The objective function can be formulated as the following.

$$\underset{s1,s2}{MAX}\ NPV = P\beta\sum_{i=1}^{N} q_i(s_1,s_2,K) - aC(s_1,K) - bC(s_2,K) - WC_{11} - WC_{12} - \frac{WC_{21}+WC_{22}}{(1+r)^{20}}$$

s_1 = the transmission factor (main line) such that $0 \le s_1 \le 2$

s_2 = the transmission factor (branch line) such that $0 \le s_2 \le 1$

$aC(s_1,K)$ = cost *a* miles main transmission line capacity s_1K MW built in year 0

$bC(s_2,K)$ = cost *b* miles branch transmission line capacity s_2K MW built in year 0

WC_{11} and WC_{12} = cost of the wind turbines built in year 0 (1st and 2nd farm respectively)

WC_{21} and WC_{22} = cost of the wind turbines built in year 20 (1st and 2nd farm respectively)

$q_i(s_1,s_2,K)$ = the expected delivered wind power at hour i from both wind farms

Note that $q_i(s_1,s_2,K) = q_{1i}(s_1,K) + q_{2i}(s_2,K)$ and $q_i(s_1,s_2,K) \le s_1K$. $q_{1i}(s_1,K)$ is the power generated by the 1st farm. $q_{2i}(s_2,K)$ is the delivered power from the 2nd farm such that $q_{2i}(s_2,K) \le s_2K$.

Let $\sum_{i=1}^{N} q_i(s_1,s_2,K) = Q(s_1,s_2,K)$ and $WC_{11} + WC_{12} + \frac{WC_{21}+WC_{22}}{(1+r)^{20}} = WC$. The objective function can be written as;

$$\underset{s1,s2}{MAX}\ NPV = \beta PQ(s_1,s_2,K) - aC(s_1,K) - bC(s_2,K) - WC$$

First order conditions;

$$\frac{\partial NPV}{\partial s_1} = \beta P \frac{\partial Q(s_1, s_2, K)}{\partial s_1} - a \frac{\partial C(s_1, K)}{\partial s_1} = 0$$

$$\frac{\partial NPV}{\partial s_2} = \beta P \frac{\partial Q(s_1, s_2, K)}{\partial s_2} - b \frac{\partial C(s_2, K)}{\partial s_2} = 0$$

From first order conditions, we can solve for the optimal value of s_1 and s_2. Similar to the 1-farm model, the functional form of $Q(s_1, s_2, K)$ cannot be formulated explicitly. The optimal size of the transmission line is solved numerically.

The data described above from 4 wind farms is used to maximize profit in this arrangement where 2 wind farms share the same central transmission line. We examine each of the 12 possible pairs. Note that the pair AB means that the main transmission line goes to A, with a secondary line to B. A is the 1st farm and B is the 2nd farm. The results from AB and BA are different as shown in Appendix C, Result 4. The model is solved with different lengths of the transmission line connecting the 1st and the 2nd wind farm.

- Scenario 1: a = 1,000 miles and b = 200 miles
- Scenario 2: a = 1,000 miles and b is the actual distance between the wind farms
- Scenario 3: a = 1,000 miles and b is calculated from the relationship between correlation and distance (Appendix A). Farm A is paired with a fictitious wind farm whose capacity factor is the same as A, but whose correlation between the outputs of the two wind farms is determined by the distance between them.
- Scenario 4: This scenario is scenario 3 with minimum output delivery requirement on the wind farm.

In scenario 3, given the correlation-distance relationship that we estimate from the wind speed data, we vary the correlation over the relevant range, calculate the implied distance, and then optimize the capacity of the transmission line to maximizes profit.

From scenario 3, Scenario 4 imposes a penalty per MWh when the delivered power from the wind farms falls below a stipulated level. We then re-optimize the transmission capacity.

3.1 Result

In scenario 1, the length of the second transmission line is 200 miles for all wind farm pairs. The pairs that have higher output correlation tend to have higher transmission capacity than the pairs with lower correlation. Profit and delivered output from each project also depend on the capacity factor of the wind farms. Project AB and BA have higher profit than other pairs because both farm A and B have a high capacity factor (33 and 35% respectively), while project CD and DC have lower profit and a lower capacity factor (both 30%).

In scenario 2 (Appendix 3, Result 2), the length of the transmission line is the actual distance between wind farms. The results also show that the wind farm pair with lower correlation needs lower transmission capacity to deliver output. In addition, when the length of the second transmission line is shorter, capacity of the line (s_2) is higher. A shorter line translates to lower cost, which makes a slightly higher capacity more profitable. In addition, like the first scenario, capacity factor is also the key factor that determines profit from the project.

In both scenarios 1 and 2, the pair of wind farms having the lowest correlation tends to have higher utilization rate of the main transmission line. This can be considered as the effect of output smoothing by aggregating wind farms with low output correlation. The transmission line is used more efficiently in the project having wind farms with low output correlation.

In scenario 1, the second wind farm is only 200 miles away, only 1/5 the distance of the transmission line from the first wind farm to the customer. If the output from the two wind farms had a correlation of 1.0, the second wind farm would be providing somewhat more expensive power than the first and the optimal capacity of the main transmission line would fall as a percentage of the sum of the two wind farm capacities (the distance of the second wind farm from the first would be partially offset by the economies of scale in transmission). The lower the correlation, the higher the optimal transmission capacity.

The shape and characteristic of the supply curve for this model are similar to the single wind farm model. Figure 10 shows the supply curve for project AB in scenario 1. Assuming that the wind farm and transmission line have been built, the wind farm owner will not produce any output if price is lower than 82 $/MWh, the price at which price equals cost.

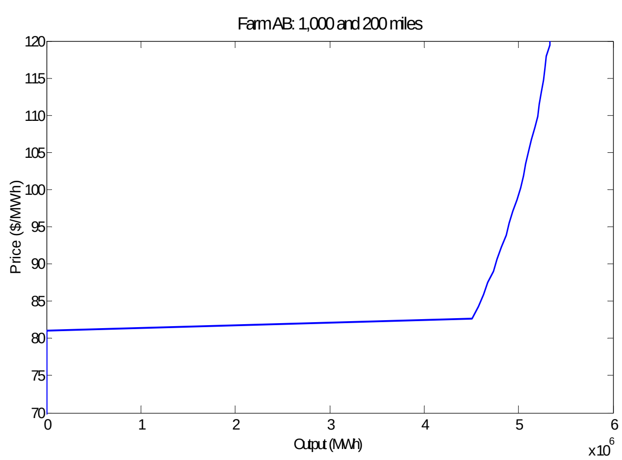


Figure 10: Supply curve from project AB in scenario 1

Figure 11 shows the relationship between price and unit cost at the profit maximizing output. The intersection is the break even price which is around $158/MWh lower than the case of 1 wind farm ($180/MWh). For 2 wind farms project, the investor will invest if price is greater than $158/MWh.

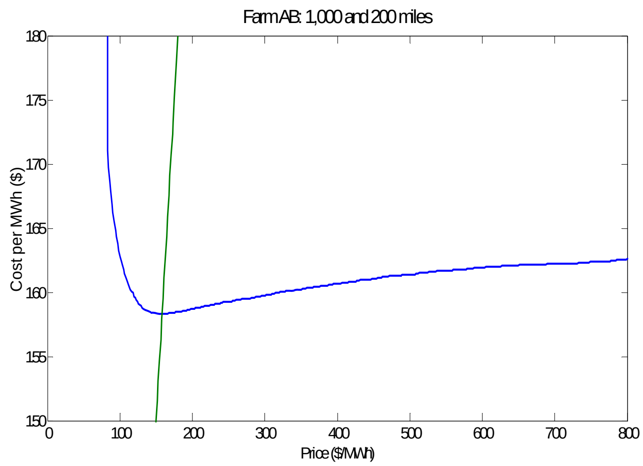


Figure11: Price and unit cost at profit maximization output

In scenario 2, the total cost of wind power is from $151 – 175/MWh. Cost of wind turbines is from $69 - 80/MWh. Cost per MWh of the wind turbine is approximately the same as cost in the model with 1 wind farm and 1 transmission. The transmission cost/MWh of the model with 2 wind farms is lower due to economy of scale in transmission investment. However, this cost saving depends largely on the length of the second transmission line. By bundling 2 wind farms, the capacity of the main transmission line is almost double compared with 1 wind farm case. Economy of scale benefit from building the large main transmission line decreases when the length of the second transmission line increases.

In scenario 3, Farm A is paired with a wind farm of the same capacity, but we vary the distance (and thus the correlation between their outputs) between the two farms. The correlation is calculated from the relationship between distance and correlation estimated in Appendix A. The simulated data used in scenario 3 are random numbers generated from the Weibull distribution (which is generally used to characterize wind data Manwell et al. (2002)).

As before, lower output correlation implies lower transmission capacity and higher transmission (main line) utilization rate, but the utilization rate is not sensitive to the correlation: correlation 0.30 has utilization rate 54% while 0.80 has utilization rate 51%. In this case, the shorter distance between farms is more important than a low correlation in profit terms. The effect of output correlation on the reliability of power output will be investigated in scenario 4.

Scenario 4 analyzes the effect of imposing a floor of 400 MW on delivered power in order to enhance reliability. If the wind farm cannot fulfill the requirement, it has to buy power from other generators or pay the system operator the ancillary services cost. This cost is defined as the imbalance price. In addition, this imbalance price is assumed to be not less than the price paid to the wind generator.

As expected, the pair with lower correlation has lower imbalance output. In addition, the result from this scenario shows the different investment decision from scenario 3. In scenario 3 without the reliability penalty, the wind farm projects with high output correlation and short transmission line are more profitable. Imposing the reliability requirement increases the distance between wind farms, resulting in an optimal output correlation in the range 0.4 – 0.6. As the delivery requirement increases, the project with high correlation wind farms is less profitable.

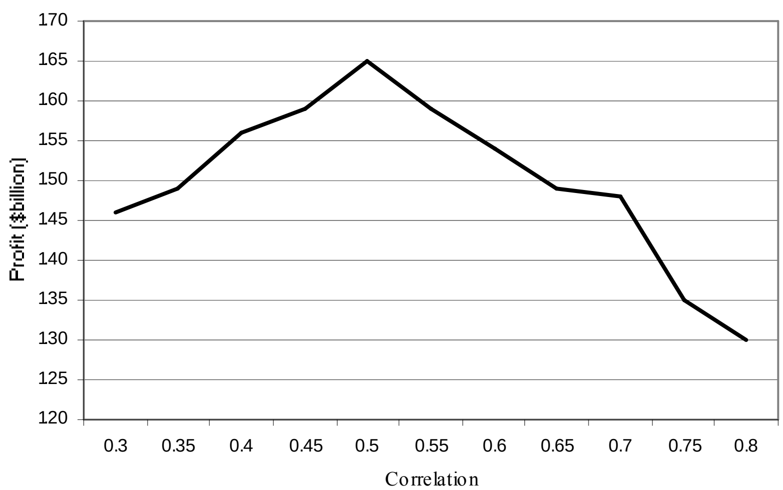


Figure 12: Profit at penalty 200$/MWh and minimum delivery level 400 MW

4. Profit analysis

From the results in the previous section, the optimal transmission capacity is less than the capacity of the wind farms. For example, transmission capacity for farm A in scenario 2 (1 farm with 1,000 miles transmission line) is around 75% of wind farm capacity. In addition, this transmission line can deliver almost 96% of total generated wind power. It means that if the transmission line is built at full capacity, the additional 25 percentage points of the line capacity can delivery only the additional 4 percentage points of wind power.

Table 3: Profit analysis

Farm	Transmission factor (s)	Transmission cost	Additional transmission cost	Additional revenue	Decrease in profit
A	0.7447	2.5905×10^9	4.7921×10^8	2.3947×10^8	2.3974×10^8
B	0.7665	2.6339×10^9	4.3581×10^8	1.9612×10^8	2.3969×10^8
C	0.7010	2.5019×10^9	5.6786×10^8	3.3604×10^8	2.3182×10^8
D	0.6919	2.4831×10^9	5.8661×10^8	2.2497×10^8	3.6164×10^8

Table 3 shows the profit loss when the transmission line is built at full capacity (the wind farm' nameplate capacity). Profit loss is calculated from the difference between additional cost of building the line at full capacity and revenue from additional delivered wind power (in present value term). The results indicate that building the line at full capacity generate the significant amount of lost to the owner.

Conclusion

Using the actual distribution of electricity production from four wind farms in the northeastern United States whose capacity factors are 29-34%, we calculated the optimal size of the transmission line connecting the wind farms to distant customers. For a distance of 500 miles, the optimal transmission capacity is about 86 %; for a 1,000 mile separation, the optimal transmission capacity is 75 %. Building a line at full capacity would increase transmission cost almost 15 % while transmitting only about 4% more electricity to the customer.

For a western wind farm with a capacity factor of 50%, the optimal transmission line would have 89 % of the capacity of the wind farm at 500 miles and 85 % at 1,000 miles.

When two wind farms use the same central transmission line, the optimal transmission capacity varies with the correlation between the outputs of the two wind farms. For a correlation of -1,0, the optimal capacity is 1.00, while for a correlation of 1.0, the optimal capacity is slightly more than 75%. The correlation between the outputs of wind farms depends, among other factors, on the distance between wind farms. We estimate that relationship and use it to optimize the location of a second wind farm. The cost of the transmission line between the two farms largely offsets the benefit of a lower output correlation, since the profit maximizing distance between the two wind farms has little effect on the cost of delivered electricity. Somewhat surprisingly, adding a second wind farm does little to lower the transmission cost of delivering power to the customer. The cost saving from bundling 2 wind farms largely depend on the distance between the wind farms.

Finally, we model a system where the owner is penalized $200/MWh whenever delivered output falls below 400 MW. In this case, the penalty means that the second wind farm increases profit and should be located further from the first to maximize profit. Bundling wind farms with low correlation can smooth output distribution and increase reliability of the delivered output. However, the developer needs to trade off between the increase in transmission cost and reliability of the delivered output.

The cost of delivered electricity varies little whether there is one or two wind farms on the transmission line. Using current estimates of the cost of a wind turbine and the cost of a transmission line, we estimate that the cost of delivered power from a wind farm with about 33% capacity that is locate 1,000 miles from the customer will be about $150/MWh with almost 2/3 of the cost due to transmission. This cost does not include measures to solve the moment to moment variability of wind turbine output or the intermittency of output. If the latter cost were imposed for power output less than 40% of wind farm capacity, profit of the wind farm decreases significantly especially for the pair of wind farms with high output correlation.

Appendix

Appendix A: Relationship between distance and wind speed (output) correlation

We use the wind speed data from 9 wind speed observation sites in Colorado (UWIG, 2007). The data from Site 205 is discarded because it has too many missing observations. The wind speed data used in the estimation is the hourly data from January 1, 1997 to January 1, 1998 totaling 8,785 observations. Wind speed data used in the calculation was measured at 25 meters level. After deleting the missing observations, we have 3,909 observations to calculate the correlation coefficients between each pair sites.

However, UWIG (2007) does not provide the distance data between each pair of wind sites. The distance between each pair of wind sites is calculated from the longitude and latitude of the wind site by using the Latitude/Longitude Distance Calculator provided by National Oceanic & Atmospheric Administration (NOAA), (http://www.nhc.noaa.gov/gccalc.shtml).

According to Manwell et al (2002), wind power (P) per area (A) is the function of the wind speed (V) and air density (ρ).

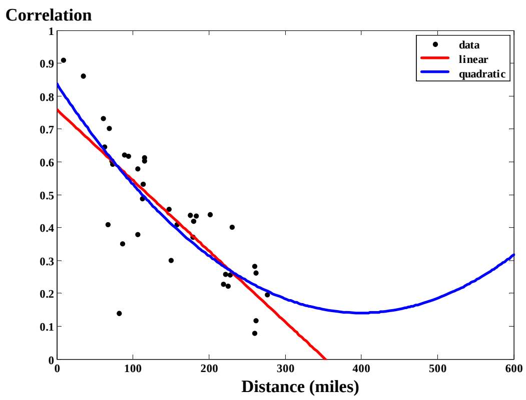
$$\frac{P}{A} = \frac{1}{2}\rho V^3$$

From the wind power formula, wind power is the cubic function of the wind speed. The cut-in[1] speed and the cut-out speed of the wind turbine is 4.5 m/s and 30 m/s respectively (Gipe, 2004). In calculation of V^3, wind speed that is lower than the cut-in speed or higher than the cut-out speed is set to be 0. We calculate the correlations coefficients of the cubic wind speed 3 (V^3) among the wind speed observation sites. Given that other variables in the formula (A and ρ) held constant, these coefficients are used as the estimated correlation coefficients of wind power among the wind sites.

Various models of distance and correlation are estimated including linear, quadratic and linear-log (correlation is a function of log(distance)). Ordinary Least Square (OLS) is used for the estimation. There are 36 observation used in estimation. The linear-log model which was used by Namovicz (2003) is more suitable than the linear and quadratic models. From figure A1 below, the linear model shows the negative relationship between correlation and distance but correlation

[1] From Gipe (2004), cut-in wind speed is the wind speed that a wind turbine start to generate power. The wind turbine cannot generate power if the wind speed is lower than the cut-in level. Cut-out wind speed is the wind speed at which the wind turbine stops generating electricity in order to protect the equipment from an excessive wind speed. The wind turbine cannot generate power if the wind speed is higher than the cut-out level.

goes to 0 as the distance increases to around 350 miles which is not true in most cases. The quadratic model shows the negative relationship in the range of distance between 0 – 400 miles but after this range correlation increases as the distance increases.



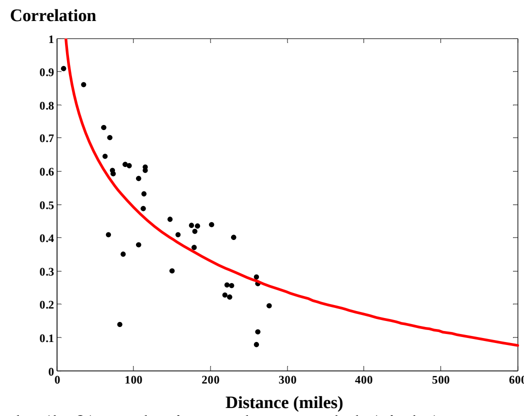


Figure A1: Linear and quadratic models (left) and Linear-log model (right)

The linear-log model, correlation = a + b*log(distance), seems best for this study. The shape of the curve is similar to the curve from NREL (2007).

<u>Estimation result</u>

Correlation = 1.557018 – 0.231544*log(distance)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	1.557018	0.145054	10.73408	0.0000
log(distance)	-0.231544	0.029868	-7.752362	0.0000
R-squared	0.638679	F-statistic		60.09911
Adjusted R-squared	0.628052	Prob(F-statistic)		0.000000
S.E. of regression	0.123475	Durbin-Watson stat		1.446861
Sum squared residual	0.518366	Log likelihood		25.24887

Appendix B: Transmission cost function estimation

The data used for transmission cost function estimation is from DOE (2002). The data from DOE (2002) was from a 1995 study. While the data are old, the economy of scale property should still be preserved in that data. The data is adjusted to reflect the current cost of transmission construction by multiplying it by 4.5..

Dependent Variable: log(cost)

Observations: 9

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	10.95961	0.298873	36.66978	0.0000
log(MW)	0.575873	0.056237	10.24006	0.0000
R-squared	0.937421	F-statistic		104.8589
Adjusted R-squared	0.928481	Prob(F-statistic)		0.000018
S.E. of regression	0.194477	Log likelihood		3.097459
Sum squared resid	0.264748	Durbin-Watson stat		1.814451

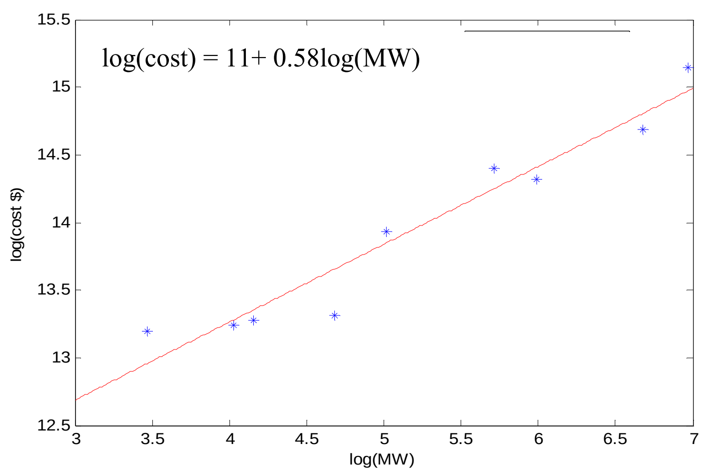


Figure B1: Transmission cost function estimation (log-linear)

Appendix C: Computation results

Farm A Output	Observed Frequency	Cumulative Observed	% Observed
0.10	1,364	1,364	31.23
0.20	598	1,962	13.69
0.30	449	2,411	10.28
0.40	375	2,786	8.59
0.50	371	3,157	8.49
0.60	288	3,445	6.59
0.70	243	3,688	5.56
0.80	279	3,967	6.39
0.90	247	4,214	5.65
1.00	154	4,368	3.53

Farm B Output	Observed Frequency	Cumulative Observed	% Observed
0.10	1,299	1,299	29.74
0.20	448	1,747	10.26
0.30	444	2,191	10.16
0.40	433	2,624	9.91
0.50	387	3,011	8.86
0.60	319	3,330	7.30
0.70	289	3,619	6.62
0.80	283	3,902	6.48
0.90	323	4,225	7.39
1.00	143	4,368	3.27

Farm C Output	Observed Frequency	Cumulative Observed	% Observed
0.10	1,473	1,473	33.72
0.20	711	2,184	16.28
0.30	485	2,669	11.10
0.40	335	3,004	7.67
0.50	318	3,322	7.28
0.60	245	3,567	5.61
0.70	208	3,775	4.76
0.80	203	3,978	4.65
0.90	177	4,155	4.05
1.00	213	4,368	4.88

Farm D Output	Observed Frequency	Cumulative Observed	% Observed
0.10	1,426	1,426	32.65
0.20	741	2,167	16.96
0.30	453	2,620	10.37
0.40	366	2,986	8.38
0.50	263	3,249	6.02
0.60	274	3,523	6.27
0.70	271	3,794	6.20
0.80	313	4,107	7.17
0.90	253	4,360	5.79
1.00	8	4,368	0.18

Table C1: Output distribution of wind farms

Result 1: 500 miles transmission line, price 200 $/MWh

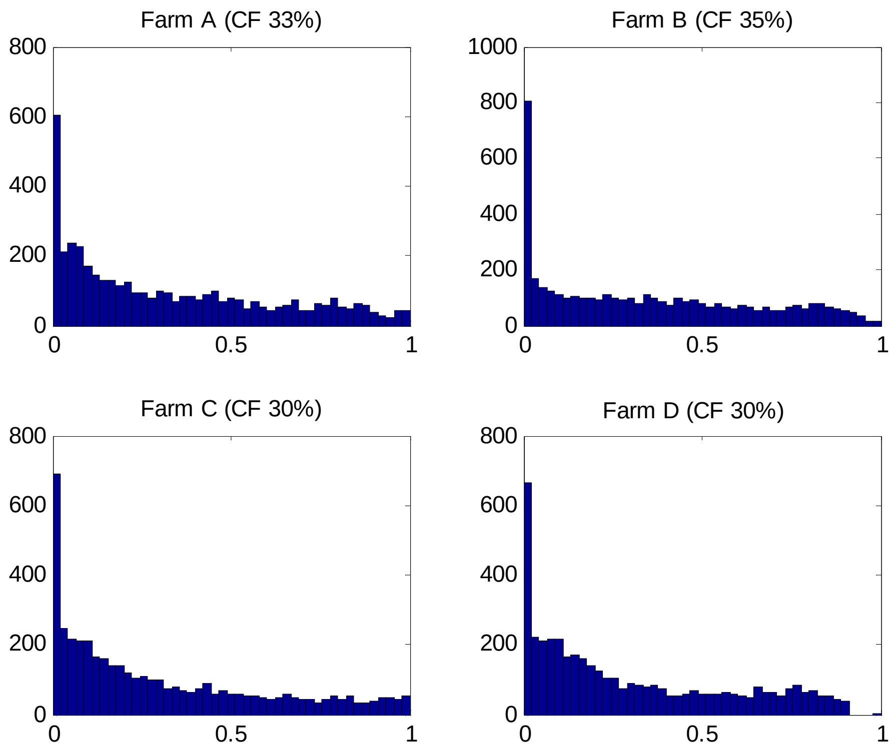
Farm	Capacity factor (%)	Transmission factor (s)	Transmission utilization (%)	Profit	Cost per unit ($/MWh)	Cost per unit (turbine)	Delivered output (MWh)	Delivered/ Generated output
A	32.73	0.8535	37.89%	1.95×10^9	126.92	70.55	1.13×10^8	98.72%
B	34.73	0.8560	40.12%	2.29×10^9	119.29	66.26	1.20×10^8	99.06%
C	29.92	0.8586	34.33%	1.47×10^9	139.49	71.42	1.03×10^8	98.40%
D	29.77	0.7944	37.10%	1.53×10^9	136.76	77.42	1.03×10^8	98.99%

Result 2: 1,000 miles transmission line, price 200 $/MWh

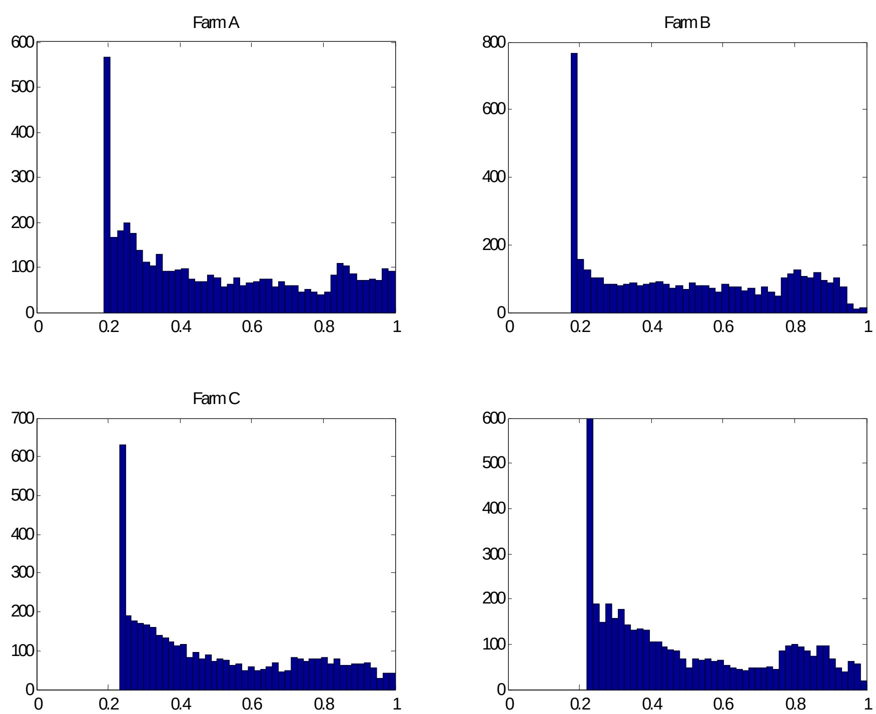
Farm	Capacity factor (%)	Transmission factor (s)	Transmission utilization (%)	Profit	Cost per unit ($/MWh)	Cost per unit (turbine)	Delivered output (MWh)	Delivered/ Generated output
A	32.73	0.7447	41.89%	5.03×10^8	180.50	72.88	1.09×10^8	95.57%
B	34.73	0.7665	43.68%	8.29×10^8	170.01	67.96	1.17×10^8	96.57%
C	29.92	0.7010	39.60%	0.39×10^8	198.29	81.74	0.97×10^8	93.18%
D	29.77	0.6919	40.95%	1.46×10^8	193.78	80.24	0.99×10^8	95.41%

Adjusted data: 50% capacity factor for 4 farms

Original data



Adjusted data (50% capacity factor)



Farm A Output	Observed Frequency	Cumulative Observed	% Observed
0.10	-	-	-
0.20	338	338	7.74
0.30	1034	1372	23.67
0.40	597	1969	13.67
0.50	450	2419	10.30
0.60	370	2789	8.47
0.70	377	3166	8.63
0.80	452	3618	10.35
0.90	487	4105	11.15
1.00	263	4368	6.02

Farm B Output	Observed Frequency	Cumulative Observed	% Observed
0.10	-	-	-
0.20	828	828	18.95604
0.30	570	1398	13.04945
0.40	457	1855	10.46245
0.50	444	2299	10.16484
0.60	409	2708	9.36355
0.70	385	3093	8.81410
0.80	420	3513	9.61538
0.90	592	4105	13.55311
1.00	263	4368	6.02106

Farm C Output	Observed Frequency	Cumulative Observed	% Observed
0.10	-	-	-
0.20	-	-	-
0.30	1176	1176	26.92
0.40	821	1997	18.80
0.50	536	2533	12.27
0.60	384	2917	8.79
0.70	318	3235	7.28
0.80	445	3680	10.19
0.90	393	4073	9.00
1.00	295	4368	6.75

Farm D Output	Observed Frequency	Cumulative Observed	% Observed
0.10	-	-	-
0.20	-	-	-
0.30	1103	1103	25.25
0.40	851	1954	19.48
0.50	551	2505	12.61
0.60	366	2871	8.38
0.70	288	3159	6.59
0.80	583	3742	13.35
0.90	527	4269	12.07
1.00	99	4368	2.27

Table C2: Output distribution of wind farms (CF 50%)

The data is adjusted by adding the same amount of output for the first 3,800 data points to achieve the capacity factor to 50%.

Result 3: 500 miles transmission line, 50% capacity factor, price 200 $/MWh

Farm	Capacity factor (%)	Transmission factor (s)	Transmission utilization (%)	Profit	Cost per unit ($/MWh)	Cost per unit (turbine)	Delivered output (MWh)	Delivered/ Generated output
A	50	0.8989	55.39%	4.78×10^9	83.56	45.82	1.74×10^8	99.6%
B	50	0.8992	55.38%	4.77×10^9	83.44	45.76	1.74×10^8	99.6%
C	50	0.9078	54.85%	4.77×10^9	83.74	45.81	1.74×10^8	99.6%
D	50	0.8686	56.67%	4.82×10^9	82.70	45.74	1.72×10^8	98.4%

Result 4: 1,000 miles transmission line, 50% capacity factor, price 200 $/MWh

Farm	Capacity factor (%)	Transmission factor (s)	Transmission utilization (%)	Profit	Cost per unit ($/MWh)	Cost per unit (turbine)	Delivered output (MWh)	Delivered/ Generated output
A	50	0.8471	58.11%	3.25×10^9	119.87	46.26	1.72×10^8	98.55%
B	50	0.8499	58.25%	3.26×10^9	119.79	46.17	1.73×10^8	98.73%
C	50	0.8322	58.80%	3.24×10^9	119.63	46.46	1.71×10^8	98.12%
D	50	0.8131	60.54%	3.33×10^9	118.06	46.23	1.72×10^8	98.62%

Result 5: Case 1: a = 1,000 miles, b = 200 miles, price 200 $/MWh

Pair	**Corr.**	**Trans (s_1)** (utilization %)	**Trans (s_2)**	**Profit**	**Cost per MWh ($)**	**Cost per MWh (turbine)**	**Delivered output (MWh)**	**Delivered/ Generated output (%)**
AB	0.7665	1.5565 (42.29)	0.8186	2.24×10^9	158.70	69.36	2.30×10^8	98.35
BA		1.5371 (42.63)	0.7935	2.24×10^9	158.51	69.61	2.29×10^8	98.39
AC	0.6919	1.4440 (41.62)	0.8111	1.49×10^9	169.88	75.87	2.10×10^8	97.18
CA		1.4388 (41.77)	0.8270	1.49×10^9	169.88	75.88	2.10×10^8	96.82
AD	0.3471	1.3207 (45.50)	0.7915	1.70×10^9	165.61	75.89	2.10×10^8	96.65
DA		1.3206 (45.51)	0.8504	1.67×10^9	166.25	75.96	2.10×10^8	96.71
BC	0.7074	1.4555 (42.67)	0.7982	1.81×10^9	164.59	73.39	2.17×10^8	97.49
CB		1.4686 (42.48)	0.8336	1.81×10^9	164.68	73.11	2.18×10^8	97.17
BD	0.3552	1.3236 (46.92)	0.7778	2.02×10^9	160.47	73.54	2.17×10^8	96.78
DB		1.3301 (46.69)	0.8560	1.99×10^9	161.13	73.45	2.17×10^8	96.71
CD	0.4572	1.3116 (43.42)	0.7799	1.20×10^9	174.32	80.08	1.99×10^8	96.06
DC		1.3034 (43.47)	0.8431	1.68×10^9	175.03	80.28	1.98×10^8	96.06

Result 6: Case 2: a = 1,000 miles, b = actual distance, price 200 $/MWh

Pair	**Corr.** (miles)	**Trans (s_1)** (utilization %)	**Trans (s_2)**	**Profit**	**Cost per MWh ($)**	**Cost per MWh (turbine)**	**Total output (MWh)**	**Delivered/ Generated output (%)**
AB	0.7665 (56.25)	1.5716 (41.88)	0.8752	2.67×10^9	150.96	69.11	2.30×10^8	98.10
BA		1.5656 (42.04)	0.8816	2.66×10^9	150.93	69.17	2.30×10^8	98.08
AC	0.6919 (18.75)	1.4614 (41.32)	0.9804	2.04×10^9	158.96	75.42	2.11×10^8	96.50
CA		1.4614 (41.32)	0.9732	2.04×10^9	158.96	75.42	2.11×10^8	96.51
AD	0.3471 (218.75)	1.3168 (45.42)	0.7821	1.65×10^9	166.66	75.97	2.09×10^8	96.65
DA		1.3188 (45.36)	0.8463	1.61×10^9	167.37	75.99	2.09×10^8	96.70
BC	0.7074 (62.50)	1.4774 (42.23)	0.9191	2.23×10^9	156.80	72.91	2.18×10^8	96.96
CB		1.4790 (42.37)	0.8883	2.23×10^9	156.75	72.89	2.19×10^8	96.98
BD	0.3552 (250)	1.3186 (46.88)	0.7662	1.88×10^9	163.19	73.64	2.16×10^8	96.78
DB		1.3271 (46.79)	0.8416	1.84×10^9	164.02	73.54	2.17×10^8	96.74
CD	0.4572 (200)	1.3719 (41.51)	0.7799	1.20×10^9	174.32	80.08	1.99×10^8	96.06
DC		1.3622	0.8431	1.68×10^9	175.03	80.28	1.98×10^8	96.06

		(41.60)						

Result 7: Case 2: 50% modified capacity factor, a = 1,000 miles, b = actual distance, price 200 \$/MWh

Pair	**Corr.** (miles)	**Trans (s_1)** (utilization %)	**Trans (s_2)**	**Profit**	**Cost per MWh (\$)**	**Cost per MWh (turbine)**	**Total output (MWh)**	**Delivered/ Generated output (%)**
AB	0.7444 (56.25)	1.7119 (58.01)	0.9314	7.93×10^9	103.08	45.94	3.47×10^8	99.28
BA		1.7101 (58.07)	0.9222	7.93×10^9	103.05	45.95	3.47×10^8	99.36
AC	0.6945 (18.75)	1.6849 (58.77)	0.9804	8.06×10^9	101.30	46.01	3.46×10^8	99.09
CA		1.6849 (58.77)	0.9732	8.06×10^9	101.30	46.01	3.46×10^8	99.10
AD	0.3184 (218.75)	1.5978 (61.97)	0.9797	7.56×10^9	107.26	46.08	3.46×10^8	99.03
DA		1.5970 (62.00)	0.9007	7.54×10^9	107.39	46.10	3.46×10^8	99.13
BC	0.7052 (62.50)	1.6827 (58.84)	0.9329	7.92×10^9	102.97	46.03	3.46×10^8	99.16
CB		1.6820 (58.87)	0.9263	7.92×10^9	102.95	46.03	3.46×10^8	99.11
BD	0.3215 (250)	1.6021 (61.80)	0.8709	7.46×10^9	108.47	46.09	3.46×10^8	99.07
DB		1.6018 (61.82)	0.8947	7.45×10^9	108.60	46.09	3.46×10^8	99.13
CD	0.4211 (200)	1.5987 (61.76)	0.8725	7.45×10^9	108.50	46.12	3.45×10^8	98.99
DC		1.5959 (61.86)	0.8910	7.44×10^9	108.63	46.16	3.45×10^8	99.12

Result 8: Farm A with different correlation farms (capacity factor 30%), a = 1,000 miles, b = distance from relationship formulated in Appendix A, price = 200 \$/MWh

Pair	**Corr. (miles)**	**Trans (s_1)** (utilization %)	**Trans (s_2)**	**Profit**	**Cost per MWh**	**Cost per MWh (turbine)**	**Delivered Output (MWh)**	**Delivered/ Generated output (%)**
A, A30	0.30 (227)	1.1342 (53.47)	0.5510	2.21×10^9	155.90	74.84	2.13×10^8	97.54
A, A35	0.35 (184)	1.1361 (53.15)	0.5422	2.26×10^9	154.70	75.24	2.11×10^8	97.43
A, A40	0.40 (147)	1.1597 (52.56)	0.5661	2.35×10^9	153.20	74.84	2.13×10^8	97.67
A, A45	0.45 (119)	1.1678 (52.20)	0.5724	2.41×10^9	152.11	74.79	2.13×10^8	97.61
A, A50	0.50 (96)	1.1881 (51.77)	0.6119	2.49×10^9	150.74	74.21	2.15×10^8	97.43
A, A55	0.55 (77)	1.1919 (51.14)	0.5926	2.47×10^9	150.91	74.72	2.13×10^8	97.58
A, A60	0.60 (62)	1.2005 (50.77)	0.5983	2.48×10^9	150.65	74.79	2.13×10^8	97.52
A, A65	0.65 (50)	1.2244 (49.78)	0.6184	2.47×10^9	150.78	74.71	2.13×10^8	97.63
A, A70	0.70 (40)	1.2439 (49.23)	0.6208	2.49×10^9	150.53	74.49	2.14×10^8	97.70
A, A75	0.75 (33)	1.2688 (48.04)	0.6344	2.45×10^9	151.37	74.64	2.13×10^8	97.75
A, A80	0.80 (26)	1.2819 (47.55)	0.6471	2.44×10^9	151.58	74.69	2.13×10^8	97.66

Result 9: Farm A with different correlation farms, a = 1,000 miles, b = distance from the relationship formulated in Appendix A, price = 200 \$/MWh, minimum delivery 400 MW

Pair	**Corr.** (miles)	**Profit @ penalty 200 \$/MWh**	**Profit @ penalty 230 \$/MWh**	**Profit @ penalty 260 \$/MWh**	**Imbalance output (MWh)**	**Delivered Output (MWh)**	**Imbalance/ Delivered output (%)**
A, A30	0.30 (227)	1.46×10^9	1.35×10^9	1.23×10^9	1.60×10^7	2.13×10^8	7.51%
A, A35	0.35 (184)	1.49×10^9	1.38×10^9	1.26×10^9	1.63×10^7	2.11×10^8	7.73%
A, A40	0.40 (147)	1.56×10^9	1.44×10^9	1.32×10^9	1.68×10^7	2.13×10^8	7.89%
A, A45	0.45 (119)	1.59×10^9	1.47×10^9	1.34×10^9	1.73×10^7	2.13×10^8	8.12%
A, A50	0.50 (96)	1.65×10^9	1.52×10^9	1.39×10^9	179×10^7	2.13×10^8	8.45%
A, A55	0.55 (77)	1.59×10^9	1.46×10^9	1.33×10^9	1.86×10^7	2.13×10^8	8.73%
A, A60	0.60 (62)	1.54×10^9	1.40×10^9	1.26×10^9	1.98×10^7	2.13×10^8	9.30%
A, A65	0.65 (50)	1.49×10^9	1.35×10^9	1.20×10^9	2.08×10^7	2.13×10^8	9.77%
A, A70	0.70 (40)	1.48×10^9	1.33×10^9	1.18×10^9	2.14×10^7	2.14×10^8	10.00%
A, A75	0.75 (33)	1.35×10^9	1.19×10^9	1.02×10^9	2.33×10^7	2.13×10^8	10.94%
A, A80	0.80 (26)	1.30×10^9	1.13×10^9	0.96×10^9	2.41×10^7	2.13×10^8	11.31%

Result 10: Farm A with different correlation pairs, a = 1,000 miles, b = distance from the relationship formulated in Appendix A, price = 200 \$/MWh, minimum delivery 500 MW

Pair	**Corr.** (miles)	**Profit @ penalty 200 \$/MWh**	**Profit @ penalty 230 \$/MWh**	**Profit @ penalty 260 \$/MWh**	**Imbalance output (MWh)**	**Delivered Output (MWh)**	**Imbalance/ Delivered output (%)**
A, A30	0.30 (227)	8.23×10^8	6.15×10^8	4.06×10^8	2.95×10^7	2.13×10^8	13.85%
A, A35	0.35 (184)	8.41×10^8	6.28×10^8	4.15×10^8	3.01×10^7	2.11×10^8	14.27%
A, A40	0.40 (147)	9.02×10^8	6.85×10^8	4.68×10^8	3.06×10^7	2.13×10^8	14.37%
A, A45	0.45 (119)	9.27×10^8	7.05×10^8	4.83×10^8	3.14×10^7	2.13×10^8	14.74%
A, A50	0.50 (96)	9.77×10^8	7.49×10^8	5.22×10^8	3.22×10^7	2.13×10^8	15.11%
A, A55	0.55 (77)	9.17×10^8	6.84×10^8	4.52×10^8	3.29×10^7	2.13×10^8	15.45%
A, A60	0.60 (62)	8.53×10^8	6.09×10^8	3.65×10^8	3.45×10^7	2.13×10^8	16.20%
A, A65	0.65 (50)	7.87×10^8	5.34×10^8	2.81×10^8	3.58×10^7	2.13×10^8	16.81%
A, A70	0.70 (40)	7.79×10^8	5.22×10^8	2.64×10^8	3.64×10^7	2.14×10^8	17.01%
A, A75	0.75 (33)	6.36×10^8	3.65×10^8	0.93×10^8	3.84×10^7	2.13×10^8	18.03%
A, A80	0.80 (26)	5.58×10^8	2.77×10^8	4.72×10^6	3.98×10^7	2.13×10^8	18.69%

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