Using Energy Storage With Wind Energy For Arbitrage

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Abstract: The potential for energy storage to directly augment the value of wind energy is well recognized [1, 2]. In particular, storage can time-shift wind output to either mitigate wind forecasting errors or deliver energy at a time when electricity prices are higher. Also, as part of a combined wind and energy storage project, energy storage can contribute significant revenue not inherently related to wind, such as by providing ancillary services [3]. The full spectrum of potential benefits should be considered when assessing the merits of combining energy storage with wind. However, analysis of any particular benefit may be rather complicated [4], making it sometimes desirable to analyze benefits separately, especially in preliminary feasibility analyses.

This paper addresses the enhancement of wind energy revenue by using storage to time-shift energy to periods of higher price, i.e., arbitrage. It does not address the other benefits of storage mentioned above. Although the initial intent was to analyze the simultaneous hour-by-hour operations of wind and storage, it was found more appropriate to analyze separately the operating benefits of wind output and of arbitrage by storage, then combine the results. This paper describes the approach used, including key assumptions and limitations. Example analyses were done using a realistic wind output distribution and historical ISO energy prices to calculate the potential arbitrage value added by storage. Results are presented for the example cases.

1. INTRODUCTION

Wind energy sold into bulk electricity markets often receives lower than average energy prices. One reason is that errors in forecasting wind can lead to substantial energy imbalance penalties [5]. Methods to mitigate such penalties have been studied, including use of storage to time-shift the wind thereby offsetting forecast errors [6] and improved wind forecasts [5].

A second reason is that diurnal variations in wind are often negatively correlated with energy prices [7], i.e., wind output often tends to be greater at times of lower energy prices, as shown in Figure 1. Energy storage can be combined with wind turbines to time-shift the delivery of energy to the power grid until a time when market prices are higher. Use of storage in this fashion can substantially increase the value of the energy delivered to the power grid, despite some energy losses due to efficiency of the storage cycle. For the date in this figure, the revenue per installed MW is for wind $275 and for storage $512 for sales less $364 charging for net $148.

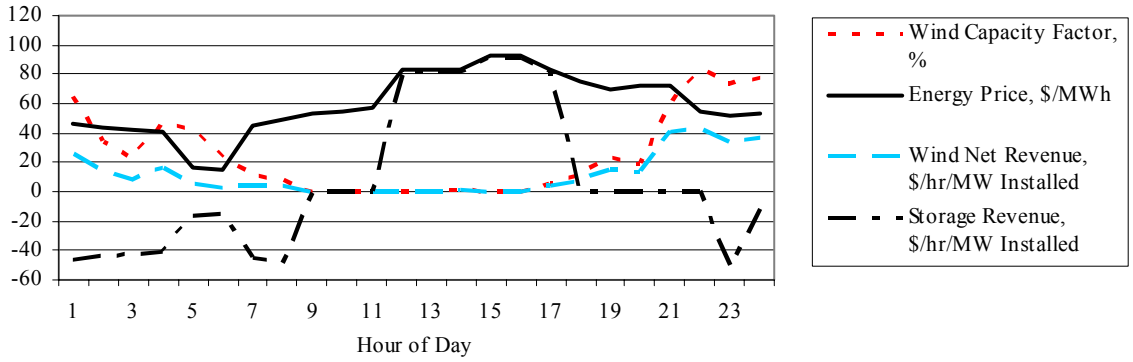

Figure 1 Diurnal Price and Revenue Variations

For maximum benefit of a combined wind and storage project, the storage unit should operate in a variety of modes at different times according to whichever mode is most profitable for the combined project. With respect to arbitrage, that implies that storage should charge from the grid whenever the price is low and the wind output

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is not sufficient to fully charge the storage unit. In general, that principle would also call for storage to supply ancillary services, but that was beyond the scope of this study.

This paper describes an approach, a model, and example results of a TVA analysis of operating benefits when energy storage is added to a wind farm in order to postpone the delivery of output until a time of day when energy prices are higher.

2. SELECTION OF OPERATING MODES

From the perspective of the wind farm, determining whether to sell wind output to the grid or use it to charge storage is a daunting task. The task was made simpler by adopting the perspective of storage (should storage charge with wind output or with energy from the grid?), by the use of two key assumptions, and by TVA's existing Storage Evaluation model which analyzes arbitrage operation of energy storage.

The two key assumptions regarding operating modes are: (1) energy transfers between the wind farm and the storage facility are valued at the coincident market price of bulk electricity, and (2) transmission losses and constraints do not influence the selection of operating modes for wind and storage. With these assumptions and by considering separately each of the possible combinations of operating modes for wind and for storage, it can be shown that operation of the energy storage unit is indifferent to whether it is charged with wind output or with energy from the grid. Hence, one may evaluate the wind output at hourly energy market prices, separately evaluate storage operation at those same hourly energy market prices, then add the results to find the combined value of wind and storage. This method also provides the correct allocation of the value contributed by wind and the value contributed by storage.

This approach is valid if the only interaction of storage with wind is for arbitrage. It is not expected to be valid if the storage facility has other interactions with wind, such as mitigating wind forecast errors.

3. MODEL CHARACTERISTICS

The existing Storage Evaluation model was used to determine the operating pattern and net operating benefit of storage. A new model, WindE, was developed to determine the operating benefits of the wind farm and combine the results with those of the Storage Evaluation program. Together these models analyze or accommodate the following situations:

1. Wind output valued at hourly prices for bulk energy, whether delivered to storage or to the grid.
2. Storage charges with either wind output or power from the grid.
3. 1 year of hourly data for bulk energy prices and wind speed.
4. Perfect foresight of prices and wind output.
5. Variable revenue and variable operating and maintenance (O&M) costs.
6. Determine the annual net operating benefit from wind alone and from wind with storage.
7. Allow for green price premium for wind output.
8. Account for unavailability and transmission losses for the wind farm.

The model does not currently address any of the following:

1. Fixed costs, such as capital recovery and fixed O&M.
2. Use of storage to provide ancillary services.
3. Imbalance penalties if wind output differs from forecast.
4. Renewable production tax credits, since these are after-tax.
5. Transmission constraints which might affect power transfer among wind, storage, and the grid.

Analysis is done on a per installed MW basis, both for wind and for storage. For different ratios of installed capacity, the separate benefits for wind and for storage can be scaled according for their respective installed capacity and the results added to determine the combined operating benefits.

In addition to operating revenues and costs, the model also calculates a price ratio which is defined as the ratio of the weighted average energy price received by wind to the unweighted average energy price for the same time period. The price ratio is an indicator of the degree to which the peak wind conditions coincide with peak

energy prices. This coincidence, or lack thereof, can significantly impact the value of wind output. Once the price ratio is known for a given set of data, it can be used in simple hand calculations to determine the change in net or gross operating revenue which would result from changes in capacity factor, electricity market prices, or variable O&M.

4. INPUT DATA FOR EXAMPLE ANALYSES

The diurnal and random variations in wind speed and electricity prices are the sources of the potential operating benefit that can be achieved by combining energy storage with wind energy. Economic analysis needs input which properly represents these variations across all seasons and multiple years. Hence, one needs not only good long term forecasts of overall wind output but also good long term forecasts of energy prices and how the wind output correlates with those prices. Different methods may be used to develop such input. However, for any given analysis, the choice of method may be determined primarily by the nature of data available.

Input Regarding Wind

The example cases used projections of Buffalo Mountain wind speeds developed for TVA by AWS Scientific. The projections were derived from actual hourly site data recorded over approximately a two year period in 1984-1986. Mean wind speeds for each month were calculated using data for the entire period. The occurrence of a given month which had the most complete actual data was chosen to represent that month. The hourly values recorded in that month were then scaled to match the average mean wind speed for the month. The wind speed values were also extrapolated vertically to 65 meters using the site mean wind shear exponent of 0.24.

Other inputs used were the Vestas V-47 wind turbine power curve with 65 m hub height (the type installed at TVA's Buffalo Mountain site), $5/MWh variable O&M, 100% turbine availability, and no transmission losses.

Input regarding Electricity Prices and Energy Storage

Published energy price data was used in order to allow open discussion of the effect of these prices upon results, despite the geographic separation this entailed between the energy prices and the wind data. The example cases used locational based marginal prices for energy as posted publicly on the New York Independent System Operator (NYISO) web site for one year ending Nov.15, 2000. Two zones with very different prices were used in order to illustrate the range of possibilities. The Long Island (LONGIL) zone had an annual average energy price of 49.56 $/MWh. It also had high price volatility, with an annual standard deviation of 33.57 $/MWh and an average daily standard deviation of 16.90 $/MWh. In contrast, the Ontario Hydro (O H) zone had a much lower annual average price of 30.89 $/MWh. Its price volatility was also much lower, with an annual standard deviation of 14.23 $/MWh and an average daily standard deviation of 8.43 $/MWh.

The Storage Evaluation program was run for each of these sets of prices to provide reference cases for use by WindE. All the Storage Evaluation reference runs modeled a storage unit with 65% efficiency, $1/MWh variable O&M, and operating power level the same whether charging or discharging.

Monthly Variability in Energy Price and Wind

Figure 2 illustrates the monthly variations in energy prices, wind capacity factor, and wind price ratio for the Long Island zone case. The large variations in capacity factor have a major effect upon the revenue earned by wind. In this example, the wind capacity factor unfortunately is lowest in summer months when energy prices are highest. A diurnal storage cycle cannot mitigate this seasonal mismatch. The annual average capacity factor is 36%. The annual average price ratio is 93%. The variations in price ratio are significant, but much less so than the capacity factor variations.

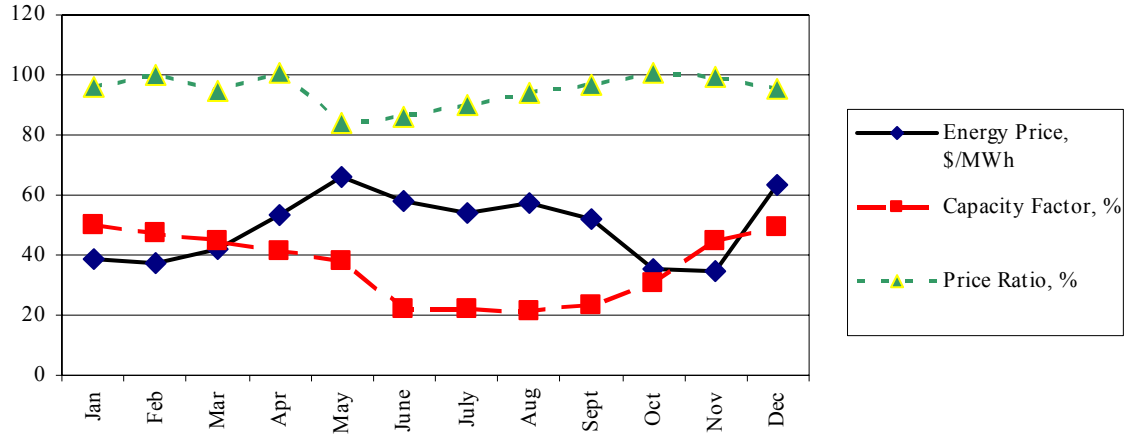

Figure 2. Monthly Price and Wind Variations for NYISO Long Island Example

5. RESULTS OF EXAMPLE ANALYSES

Figure 3 shows variations throughout the year in the values contributed by wind and by storage based on Long Island zone energy prices. The monthly fluctuations in value of wind are the result of variations in the wind itself, in the average market price of electricity, and in the monthly correlation of wind with energy price. The value of storage is strongly affected by the daily volatility in the electricity market price and is also affected by the overall electricity market price. The value of storage benefits shown in Figure 3 for any specific month may fluctuate considerably from year to year. That is because a large percentage of the storage value is likely to be derived from only a few brief periods of very high volatility, and the timing of such periods is unpredictable.

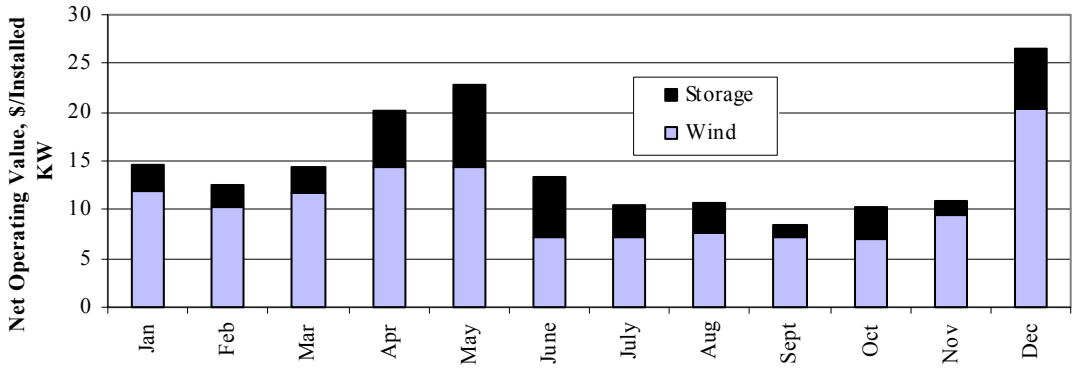

Figure 3 Monthly Operating Value for Long Island Zone

Figure 4 shows the summary results for a full year for energy prices in both the Long Island and the Ontario Hydro zones. The potential benefit available from a green price premium and from a production tax credit have been included in Figure 4 for illustration, despite accounting differences applicable to before- and after-tax numbers. For this figure, the production tax credit was assumed to be 1.7 cents per kwh produced and the green price premium was assumed to be 2.5 cents per kwh produced. Green premiums in energy-based programs have been reported as low as 1 cent/kwh with a median of 2.5 cents/kwh [8].

Since both cases used the same data set for wind speed throughout the year, the differences in results are due purely to differences in energy prices in the two zones. As expected based on average energy prices, the wind output would be much more valuable in the high price Long Island zone than in the Ontario Hydro zone. It is interesting to note that there were occasions (although very few) when the electricity price in each of the zones

was less than the wind turbine variable O&M cost, indicating that the wind turbines were uneconomical to operate during those hours unless tax credits and/or a green pricing premium were applicable.

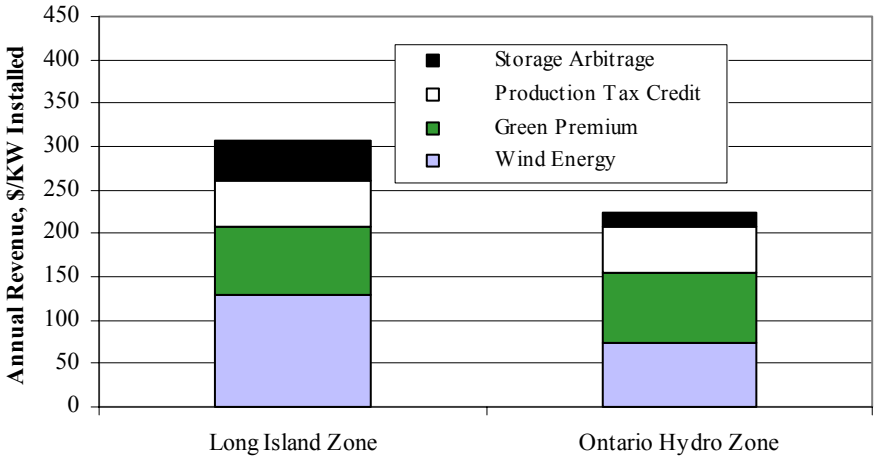

Figure 4. Potential Revenue Components for Wind

Very substantial annual revenue is available to wind farms from wind energy sold at market prices and in many cases from a green premium and from a production tax credit, even without the benefit of storage. This revenue is sufficient to justify investment in wind turbines at current capital cost levels, which is also obvious from the substantial amount of wind capacity installed in 2001 alone.

6. CONCLUSIONS

A model has been developed and applied in example cases to calculate the net operating revenue for wind based on hourly market prices, either with or without energy storage capacity used for arbitrage. The model is potentially useful for evaluating actual versus forecast economic performance of a wind farm. The model is amenable to expansion for analyzing the economic effects of wind's need for ancillary services and/or for analyzing the use of storage with wind to provide not only arbitrage but also ancillary services to the grid. The model could also be useful in analyzing the economics of importing wind energy from a long distance such that transmission losses are a significant concern.

Several observations can be made from the example analyses. Since higher overall energy market prices increase the value of wind, proximity of wind turbines to a market with high prevailing prices is an important factor in wind site selection. The diurnal correlation of wind and high energy prices can also be a significant factor.

The benefits of storage increase with higher daily volatility in energy market prices. Higher peak energy prices increase storage benefits, but higher off-peak energy prices decrease storage benefits due to charging costs and storage cycle losses.

If storage is used only for arbitrage and with the assumptions made in this model, there is no optimum ratio of storage capacity to wind capacity. The desired sizes of wind capacity and storage capacity can be chosen based on their individual merits as determined separately. An optimum size ratio likely will exist if storage interacts with wind in other ways, such as to mitigate either the ancillary services needs of wind or errors in forecasting wind. Additional modeling may be needed to address those applications.

It is also important to monitor the continuing evolution of electricity market tariffs, prices, and rules to identify any changes which could affect either wind energy or energy storage. For example, very recently FERC

approved [9] a California ISO tariff amendment which should greatly reduce the imbalance penalties which were being incurred by wind generators due to forecasting errors. Given that approval by FERC, one might expect similar changes to occur in other ISO markets.

The use of storage with wind has potential to add significant benefit from arbitrage, but in these example cases the added direct economic benefit is not likely by itself to justify installation of storage capacity. Storage may provide significant additional benefits which were not included here, such as by mitigating wind forecasting errors [6] and especially by providing ancillary services to the power grid [3]. Changing strategic situations may in the future alter economic conditions and provide additional incentives to deploy storage along with wind. Examples of such possible strategic factors are renewable portfolio standards, a carbon tax, and market penetration by wind sufficient to affect the diurnal market pricing of electricity.

The overall benefits may be sufficient to justify installation of energy storage in conjunction with wind. Future improvements in storage technologies, such as reductions in capital cost and improvements in storage cycle efficiency, are also expected to make energy storage more attractive for this and other purposes.

8. REFERENCES

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