Minimizing Wind Power Producer's Balancing Costs Using Electrochemical Energy Storage

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MINIMIZING WIND POWER PRODUCER'S BALANCING COSTS USING ELECTROCHEMICAL ENERGY STORAGE

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Jarmo Partanen (LUT), Bri-Mathias Hodge (NREL)

SUMMARY

In this paper the question of how the electrochemical energy storage can be used to decrease the balancing costs of a wind power producer in the Nordic market is studied. Since the electrochemical energy storage is developing in both technological and financial terms, a sensitivity analysis was carried out for the most important variables the wind-storage hybrid system. The system was studied from a wind power producer's point of view. The main result is that there are no technical limitations to using storage for reducing the balancing costs. However, in terms of economic feasibility, installing hybrid wind-storage systems like the one studied in this paper faces challenges in both the short and long terms.

One of the stated benefits of electrochemical batteries is said the ability to also help in integrating wind power into the power system. However, using storage to even out the uncertainty of day-ahead forecasts can only provide 50% of the balancing energy with a 1 MW energy storage system and a 12 MW storage system is required to balance 75 %, with higher associated investment costs.

KEYWORDS

Wind power, Energy storage, Wind power forecasting, Balancing, Batteries, Battery Systems

1. INTRODUCTION

Wind power has a variable and uncertain nature, which causes difficulties in predicting power output in the day-ahead horizon. In the Nordic market wind power participates in the market together with conventional generation. Therefore, wind power producers have to deal with their own imbalanced energy from inaccurate forecasts. Thus, their share of imbalance costs is much larger than for controllable conventional generation. One way to decrease balancing costs is to install electrochemical storage next to a wind turbine site, the purpose of which is to reduce the amount of imbalance energy. In this paper this kind of hybrid wind-storage setup is studied and its economic feasibility is examined.

2. MARKET MODEL

The studied area in this paper is a site from Finland and thus the market model and rules from Nord Pool are used. In Nord Pool there are two places to trade physical electricity delivery, day-ahead and intraday markets. In the day-ahead market the bids for the coming day's delivery hours must be submitted before 1 pm Finnish time [1]. The area prices are then determined based on the crossing point of demand and supply curves while considering the constraints in the transmission system. The intraday trading begins immediately after the day-ahead prices are announced for the delivery hours. However, in this paper it is assumed that the producer will not trade in the intraday market and only participates in the day-ahead market. The intraday market is not used for two reasons: a) the intraday market is not a liquid marketplace b) trading in the intraday market might not be beneficial, since the two price model is used for production balances [2].

In the Nordic power market producers' imbalances are punished with balancing prices, which are connected to the regulation prices. The regulation prices are formulated by the need for system regulation in the whole Nordic system, with up and down regulation separately determined. When a delivery hour has a surplus of energy down regulation bids must be activated in order to stabilize the system and down regulation prices are used to penalize producers' surplus imbalances. At the same time producers who have a deficit from the contracted energy delivery can deal with their imbalances at the day-ahead price. On contrary, when a delivery hour has a deficit of energy, up regulation bids must be activated and producers with deficit of energy must pay the up regulation price.

However, when there are transmission constraints between different price regions the local transmission system operator (TSO) is responsible for balancing the production in its area, instead of balancing the interconnected area as a whole.

2.1 Mathematical formulation of Nordic market

The revenue, ρ_k in the Nordic market can be formulated as the sum of maximum possible income from the spot market and the cost of imbalance energy, equation (1)

$$\rho_k = \pi_k^{(S)} W_k + C_k^{(\uparrow/\downarrow)} \tag{1}$$

where $\pi_k^{(S)}$ is the day-ahead price for hour *k*, W_k is the produced energy, $C_k^{(\uparrow/\downarrow)}$ is the cost imbalance for hour *k*. The imbalance cost term $C_k^{(\uparrow/\downarrow)}$ can be written as

$$C_k^{(\uparrow/\downarrow)} = \begin{matrix} \psi_k^{(\downarrow)}\left(W_k - \widetilde{W}_k^{(S)}\right), & W_k \geq \widetilde{W}_k^{(S)} \\ \psi_k^{(\uparrow)}\left(W_k - \widetilde{W}_k^{(S)}\right), & W_k \leq \widetilde{W}_k^{(S)} \end{matrix} \tag{2}$$

where unit balancing costs for down and up regulation, $\psi_k^{(\downarrow)}$ and $\psi_k^{(\uparrow)}$ can be formulated as

$$\psi_k^{(\downarrow)} = \pi_k^{(\downarrow)} - \pi_k^{(S)}$$
$$\psi_k^{(\uparrow)} = \pi_k^{(S)} - \pi_k^{(\uparrow)} \tag{3}$$

By considering how the market operates, unit balancing costs are always zero or negative.

3. BATTTERY MODEL

For analysing the state and wear-and-tear of an electrochemical battery, a simplified model of an electrochemical battery is used. The parameters included in the model are: cycle life, maximum operating life, maximum capacity, unit investment cost, and cycle efficiency. Cycle life of a battery is estimated by using the rainflow-algorithm [3], which is usually used to analyse fatigue on materials when the stress is varying. The rainflow-algorithm can provide an estimate of the frequency of different sizes of cycles that the battery goes through in its operational periods.

In this paper the relationship between cycle life and depth of charge is assumed to be linear, which applies for instance for LiFePo-tehcnology when the battery is operated in a constant environment [4]. Thus, it is assumed that the energy that the battery can charge/discharge in its lifetime is assumed to be constant. In order to know how many full cycles the battery goes through in the operational period, the so called equivalent cycles, C^{ekv} is calculated. When calculating equivalent cycles of the battery, all cycles below the battery's nominal value must be weighted by a energy dependent weight, equation (4)

$$C^{ekv} = \sum_{i=N_{min}^B}^{N_{max}^B} \frac{C_{amp}^i}{C_{max}} \cdot i \tag{4}$$

where N_{min}^B and N_{max}^B are the number of cycles that the battery does in its minimum and maximum cycle amplitude, respectively. The amplitude of a cycle is C_{amp}^i and the maximum capacity of the battery is C_{max}. Maximum operation time, L_{op} of the battery is the relation of maximum cycle life to the yearly equivalent cycles that the battery goes in a year. However, the maximum technological lifetime of a battery is assumed to be limited for cases when L_{op} exceeds maximum lifetime of a battery L_{op}^{max}.

$$L_{op} = \frac{C_{max}}{C^{ekv}/8760} \tag{5}$$

The annuity of an investment, *I* is calculated by using equation (6)

$$I_{ann} = \frac{i(1+i)^{L_{op}}}{(1+i)^{L_{op}} - 1} \cdot I \tag{6}$$

The unit capital cost of an investment is the annuity of an investment divided by the energy used, E_{bat} in the battery, equation (7)

$$U_{cap} = \frac{I_{ann}}{E_{bat}} \tag{7}$$

The capacity of a battery, C can never go under zero and it cannot exceed its nominal capacity, such that $C \in [0, C_{max}]$.

3.1 *Battery Charging*

For battery charging the prediction error, ε_k, must be positive. However, when charging there are losses due to the efficiency, δ, of the battery. Thus, the actual stored energy is:

$$\hat{\varepsilon}_k^{store} = \delta \varepsilon_k \tag{8}$$

When energy is lost, which would have been otherwise sold to the market, there is a cost ρ_{loss}, which is proportional to the down regulation price in that hour. However, charging prediction errors gives the possibility to save on balancing costs, ρ_{avoid}.

$$\rho_k^{store} = \rho_k^{avoid} - \rho_k^{loss} = \psi_k^{(\downarrow)} \varepsilon_k - \pi_k^{(\downarrow)} \hat{\varepsilon} \tag{9}$$

When there is a situation that the stored energy would exceed the maximum capacity of the battery, that portion of energy must be sold to the market as there would not be any available storage capacity.

3.2 *Withdrawing energy*

When the prediction error is negative, energy must be withdrawn from the battery in order to keep the production as close to the contracted as possible. However, when energy is withdrawn from the battery, the efficiency of the battery must be considered. Therefore, more energy must be taken from the battery to cover the prediction error.

$$\hat{\varepsilon} = \frac{\varepsilon_k}{\delta} \tag{10}$$

The avoided costs are then:

$$\rho_k^{withd} = \varepsilon_k \psi_k^{(\uparrow)} \tag{11}$$

When taking the energy from the battery there is no need to calculate the efficiency losses, as it is considered only when charging the battery.

3.3 *Energy cost*

The unit benefit of stored energy to the battery is dependent on the capital cost of the battery and the avoided costs from the balancing market. Unit benefit is the sum of avoided costs, ρ_k^{avoid} in relation to used energy in the battery, equation 12.

$$U_{ben} = \frac{\sum_{k=1}^{8760} \rho_k^{avoid}}{E_{bat}} = \frac{\sum_{k=1}^{8760} \rho_k^{store} + \rho_k^{withd}}{E_{bat}} \tag{12}$$

Therefore, the average unit cost of energy at the battery is:

$$U_{cost} = U_{ben} - U_{cap} \tag{13}$$

4. FORECAST ERRORS

It is important to understand the basic statistical properties of prediction errors when considering the impacts on storage. The distribution of prediction errors can be considered as hyperbolically distributed [5]. An international comparison of forecasting error distributions was carried out in [6] where different characteristics of forecasting errors were studied. In figure 1 an autocorrelation plot and a histogram of prediction errors with hyperbolic fit is presented. The prediction errors are strongly autocorrelated, which means that energy is usually pushed to the battery or withdrawn from the battery for multiple consecutive hours at a time. This can cause the capacity limits of the storage to be easily reached and thus the economy of the wind-storage system is reduced.

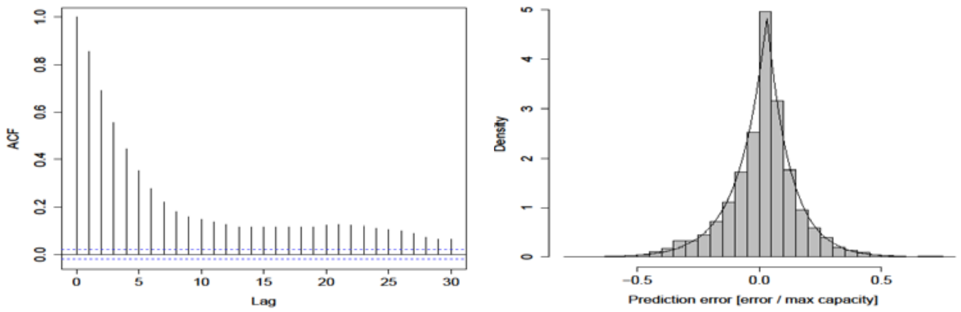

Figure 1 Autocorrelation plot and prediction error histogram with hyperbolic fit

5. SIMULATIONS

In order to study the economics of electricity storage, a sensitivity analysis was carried out to see how the average unit costs of energy (equation (13)) changes by varying some of the important parameters of the wind-storage system. Since the development of the forecasting techniques has been fast for the past decade, two different sensitivity scenarios were simulated: forecast error accuracy was improved uniformly by 10% and 50%. Besides uniform improvement to prediction errors, artificial prediction error time series were created without any autocorrelative properties to see the significance of autocorrelation in prediction errors. Besides the forecasting error accuracy, balancing prices are the other major driver why the installation of battery would be a profitable investment. However, the development of future balancing prices is not so straightforward to forecast and therefore two different scenarios were applied, a high and a low price scenario. In the high price scenario the up and down unit balancing costs were increased by multiplying each unit balancing cost with a factor of two. For the low price scenario the prices were halved. It is assumed that the spot-prices are reduced and the balancing prices remained the same, which means that the efficiency losses are dealt with at the current balancing prices.

Since development in battery technologies is ongoing and taking big leaps in terms of cost-benefit all the time, multiple different electrochemical storage related variables were varied in order to have a good understanding of how the development of batteries will affect the benefits of the wind-storage system. The varied parameters are cycle life, investment unit cost, and capacity of the battery. The future values of the parameters are based on the U.S. Department of Energy views for long term storage technology development [7].

Table 1 Modified parameters in the simulation

	starting value	end value
Cycle life [cycles]	2000	6000
Investment cost [€/kW]	1300	700
Capacity of battery [MW]	0.5	12

There are parameters that are assumed to be constant in the simulation, as seen in table 2.

Table 2 Constant parameters in the simulation

variable	value
interest rate, i	5 %
nominal capacity of wind turbine site, P_n	30 MW
round trip efficiency, δ^2	85 %
maximum battery life, L_{op}^{max}	20 years

5.1 Investment price sensitivity

In the base scenario two different unit investment prices were looked into: long-term unit investment price, 700 €/kWh and a near-term price, 1300 €/kWh. The simulations are run with the current forecasting error levels and with the current balancing prices, and the results are shown in figure 2.

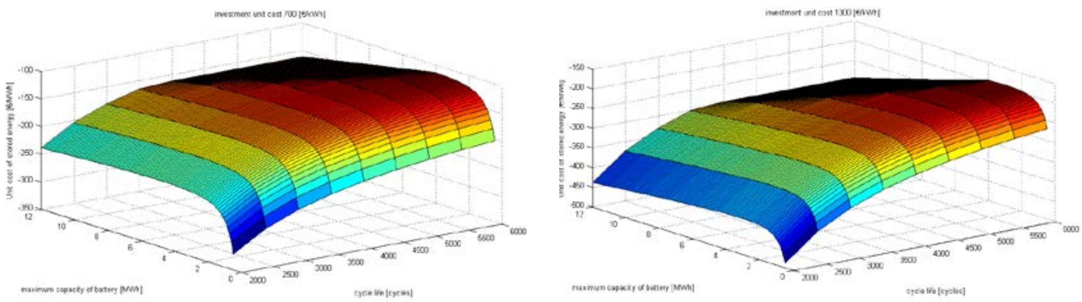

Figure 2 Unit cost of energy for two unit investment prices 700 €/kWh (left) and 1300 €/kWh (right)

The unit cost of energy is strongly negative, which means that the capital costs of the battery are much greater than the avoided costs. The profitability is always increasing, or remaining as same, when the cycle life is increased. The optimal size of battery is around 4MWh for a 700 €/kW unit investment price and for a 1300 €/MWh price it is 3 MWh. The profitability of the battery is clearly increased as the investment price is reduced.

5.2 Forecast error sensitivity

In this case different scenarios are simulated with the near term investment price scenario, 1300 €/kWh and see how the improvement in the forecast error accuracy will impact the profitability of a battery investment, as seen in figure 3.

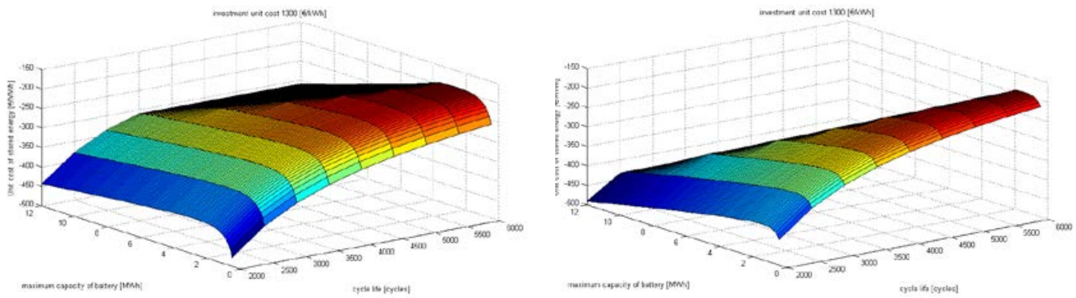

Figure 3 Unit cost of energy for two different forecasting error improvement scenarios: 10% (left) and 50 % (right)

As the forecast models' develop it will have an effect on favouring smaller energy storages since the reduction of large prediction errors will reduce the benefit of having a large storage capacity at the wind turbine site.

5.2.1 *Removing autocorrelation*

When removing the autocorrelation of prediction errors the profitability of wind-storage system does not change much when comparing to the base case scenario in the chapter 5.1. The profitability of high capacity storages are however lowered probably because the battery does not need to be used as often.

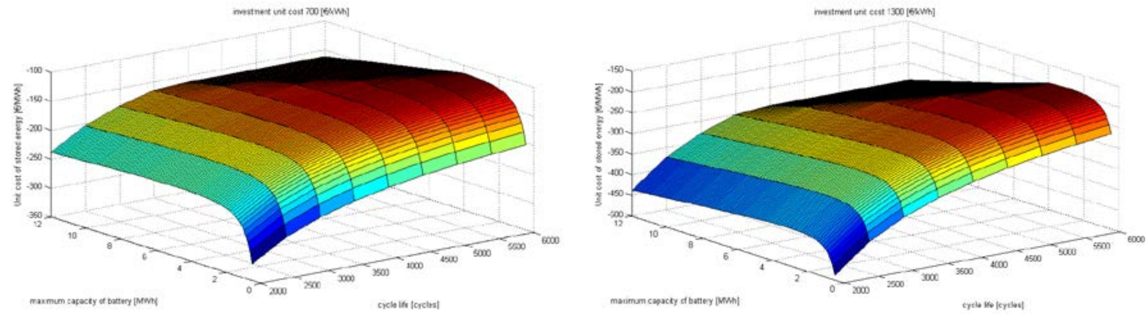

Figure 4 Unit cost of energy for two unit investment prices 700 €/kWh (left) and 1300 €/kWh (right) when the prediction errors are completely random

5.3 Sensitivity on unit balancing costs

Increasing unit balancing costs can bring additional value to the costs savings provided by the battery. However, if battery cannot store that energy it will show as an increased additional balancing cost. Therefore, the cost benefit of larger batteries will increase as the unit balancing costs are increased since larger storage size can have higher additional savings, as seen in figure 4. However, when lowering the unit balancing prices the benefit of large scale energy storages is reduced.

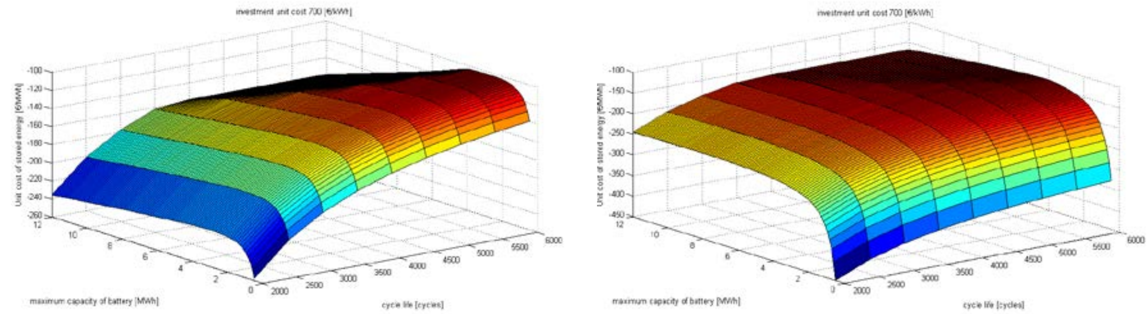

Figure 5 Unit cost of energy for two different unit balancing cost scenarios: 50% (left) and 200 % (right)

The autocorrelation of prediction errors has an impact on how efficiently it is to utilize a wind-storage system. In figure 5 we see the amount of non-balanced energy for different storage capacity sizes. It is important to notice that even having 12 MWh of storage, it is only possible to balance 65% of the imbalance energy.

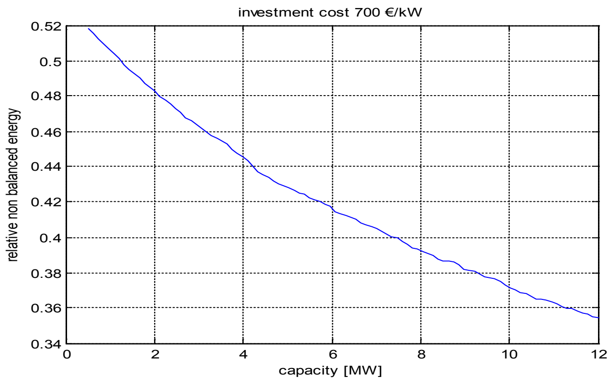

Figure 6 Non-balanced energy on different storage sizes

6. CONCLUSION

Using electro-chemical storage to balance wind power variability is an idea that would help producers to avoid balancing costs and also help the integration of variable generation to the power system. In this paper it was shown that there is currently no financial incentive to balance wind generation with electrochemical storage. It was also shown that even looking at the future expected investment prices of electrochemical storages and optimistic views of how battery technology will develop, the investment is far from profitable. The main reasons are the decreasing forecasting errors and relatively low unit balancing costs. Biased forecasts are also a big contributor to the economics of a wind-storage system. From the perspective of minimizing the total system variability and increasing the profits of single producers, it is better to have well dispersed wind turbine sites and pool the production since the correlation of prediction errors when well dispersed is very low [8].

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BIBLIOGRAPHY

[1] NordPoolSpot, “Nord Pool Spot,” 15 5 2014. [Online]. Available: http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/. [Accessed 15 5 2014].

[2] H. Holttinen and G. Koreneff, “Imbalance Costs of Wind Power for a Hydro Power Producer in Finland,” *WIND ENGINEERING,* vol. 36, no. 1, pp. 53-68, 2012.

[3] C. Amzallag, J. P. Gerey , J. L. Robert and J. Bahuaud, “Standardization of the rainflow counting method for fatigue analysis,” *Journal of Fatigue,* vol. 16, no. 4, pp. 287-293, 1994.

[4] J. Wang, P. Liu, E. Sherman, J. Hicks-Garner, S. Soukiazian, M. Verbrugge , H. Tataria, J. Musser and P. Finamore, “Cycle-life model for graphite-LiFePO cells,” *Power Sources,* vol. 196, no. 8, pp. 3942-3948, 2011.

[5] B.-M. Hodge, D. Lew, M. Milligan, H. Holttinen, S. Sillanpää, E. Gómez-Lázaro, R. Scharff, L. Söder, G. Larsén and G. Giebel, “Wind Power Forecasting Error Distributions: An International Comparison,” in *Proceedings of 11th International Workshop on Large-Scale Integration of Wind Power into Power Systems*, Lisbon, 2012.

[6] J. Zhang, B.-M. Hodge, J. Miettinen, H. Holttinen, E. Gomez-Lazaro, N. Cutululis, M. Litong-Palima, P. Sørensen, A. Lovholm, E. Berge and J. Dobschinski, “Analysis of Variability and Uncertainty in Wind Power Forecasting: An International Comparison,” in *Proceedings of 12th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Farms, WIW2013*, London, 2013.

[7] U.S. Deparment of Energy, “Grid Energy Storage,” U.S. Department of Energy, 2013.

[8] J. Miettinen and H. Holttinen, “Prediction Errors and Balancing Costs in Finland Using Short Term Prediction for Different Geographical Areas,” in *Proceedings of 12th International Workshopon Large-Scale Integration of Wind Powerinto Power Systems as well as on Transmission Networks for Offshore Wind Farms, WIW2013*, London, 2013.