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# Wind Generation Curtailment Reduction based on Uncertain Forecasts

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## SUMMARY

Wind generation can efficiently address many of the economic and environmental challenges in electric power grids, but from a technical perspective, it causes major difficulties for system operators because of its variability and the uncertainty in the forecast. From a technical perspective, however, wind generation causes major difficulties for system operators as it is variable and there is always a level of uncertainty in the forecast. Therefore, the integration of high penetration wind generation into the power system may pose a challenge. As a solution, wind generation is commonly curtailed to help reduce its variability, however, this is not the best solution from an economic perspective. This paper proposes a robust optimization model to minimize wind generation curtailment by installing battery energy storage. Using robust optimization, the wind generation forecast inaccuracy is taken into account, allowing for a more practical solution. The viability and performance of the proposed model is investigated via numerical simulations.

## KEYWORDS

Variable generation, forecast uncertainty, wind generation curtailment, battery energy storage.

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## 1. INTRODUCTION

The penetration of renewable generation is growing fast, and most researchers anticipate that renewables will be the largest source of energy in near future [1]. The developed countries offer incentives for increasing renewable generation penetration; as a result, the installed capacity of renewable generation resources has been significantly increased in recent years. Globally, wind generation is considered the largest and fastest-growing technology among renewables. In 2016, the cumulative installed wind generation capacity reached 486.8 GW up from 432.7 GW in 2015 with an increase of 12.5% [2]. The global growth of wind generation capacity is shown in Figure 1.

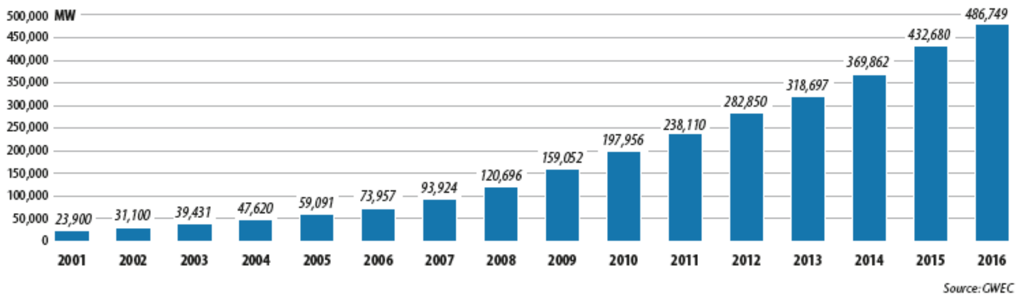


Figure 1. Global cumulative installed capacity of wind generation [2]

Wind generation is a viable generation resource as it is inexpensive and environmentally-friendly. However, it is intermittent and uncontrollable [3]. The intermittent nature of wind makes the integration of wind generation into the power system a challenge for system operators. The variable generation causes mismatch between system generation and load and could potentially cause instability. This issue will be more severe when variable generation penetration becomes high, like the case with wind generation [4]. Generation resources, dispatchable and non-dispatchable, must be carefully managed to maintain the power system generation-load balance and keep frequency at acceptable ranges [5]. As a result, the extremely variable wind generation must be mitigated to protect the power system from oversupply risk.

Wind generation curtailment has been occurring around the world. Study in [6] presents examples of wind generation curtailment in many countries and shows the reasons and methods of wind generation curtailment and how to reduce these curtailments. Figure 2 shows the wind generation curtailment in different balancing areas in the United States from 2007 to 2013. Most wind curtailment levels are below 4%. However, in some areas, such as in ERCOT territory, wind generation curtailments as high as 17% were recorded. Wind generation curtailment has also occurred in New England ISO (NE-ISO) and CAISO, which are not mentioned in Figure 2. NE-ISO reduced wind generation capability of a 45 MW wind unit in Vermont NE to only 20 MW [7]. In 2017, CAISO curtailed 60 GWh and 80 GWh of wind generation in February and March, respectively, up from 21 GWh and 47 GWh in the corresponding months of the previous year [8]. There are many solutions to overcome the wind power variability, such as installing pump hydro storage system [9], using battery energy storage system [10] and wind generation curtailment [6].

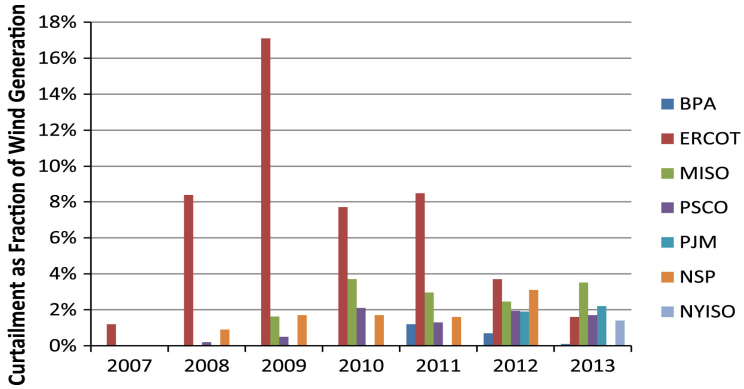

Figure 2. Wind generation curtailment in the U.S. from 2007 to 2013 [6]

The wind generation curtailment is defined as using less than what a wind turbine could potentially generate, or in other words, reducing the wind generation by preventing wind turbine to operate on maximum power point tracking (MPPT) [11]. The massive wind generation curtailment experiences mentioned above show an increase in energy waste. This energy waste is deemed less desirable and considered as a loss for both system operator and the wind farm owners. However, it is crucial to curtail the wind generation to acceptable levels under some operating conditions, such as oversupply. The acceptable curtailment levels must be calculated based on a system-based approach in order to consider the economic benefits of wind generation [6], [12]. In [6], authors present applications of wind curtailment reduction in different countries. Reducing the wind generation curtailment can be accomplished by increasing the power system flexibility through installation of battery energy storage system (BESS). The excess wind generation can be stored in BESS by the charging process for later used by discharging when wind generation is low. In [13], the previous work of authors, a model to reduce the wind generation curtailment by optimally sizing BESS and simultaneously obtaining the optimal amount of wind generation curtailment was proposed. The objective of reducing the wind generation curtailment is achieved as the curtailment is reduced by 99% by installing an optimally-sized BESS.

In this paper, authors will extend their previous work to consider the uncertainty of wind generation forecast, and thus, to further ensure practicality of the obtained solutions. The proposed model in [13] will be modified to include the impact of forecasting error of wind generation. A robust optimization approach is applied to solve the problem under worst-case wind generation accuracy conditions. The rest of this paper is organized as follows: Section 2 presents the proposed robust optimization model. Numerical analyses of the proposed model are provided in Section 3. Section 4 concludes the paper.

## 2. THE ROBUST OPTIMIZATION MODEL - OUTLINE AND FORMULATION

The main objective of the proposed model is to maximize the economic benefit of wind generation by reducing the wind generation curtailment considering forecast uncertainty. Wind generation curtailment is required under some operational conditions, and it can be achieved by using power electronic devices that help to prevent overgeneration from the wind turbine. To reduce the wind generation curtailment, the BESS is used to properly store the surplus wind generation instead of curtailing it. The BESS is capable of shifting the wind generation by charging the BESS when wind generation is oversupplied and discharging the BESS stored energy in low wind generation periods. The BESS investment cost is relatively high; as a result, it should be minimized by optimally sizing the BESS power and energy ratings and at the same time reducing the amount of wind generation curtailment. In addition, the BESS investment cost constraint is considered to prevent it from exceeding a certain investment budget. The objective function of the proposed robust optimization model is represented in (1), which minimizes the total annual system planning cost. The objective is simultaneously maximized to obtain the worst-case solution under the prevailing uncertainty of wind generation forecast.

$$\max_{\mathrm{U}} \min_{\mathrm{P}} \sum_{i}\sum_{t} F_i(P_{it}) + (P^R CP + E^R CE) \tag{1}$$

where $i$ and $t$ are the indices for dispatchable units and time, respectively. $F(.)$ represents the operation cost function of dispatchable units. $P$ is the amount of generated power by each unit. $P^R$ and $E^R$ are the BESS power and energy ratings. $CP$ and $CE$ are the annualized BESS investment cost for power and energy ratings, respectively. U and P are the uncertain parameters and primal variables, respectively. Uncertain parameters include the wind generation forecast and primal variables include the generated power by dispatchable units and the BESS size (i.e. rated power and energy variables). The robust optimization finds the worst-case solution as uncertain wind forecast varies within the uncertainty intervals. The worst-case solution is obtained by maximizing the minimum value of total planning cost over the uncertain parameter (i.e. the wind generation). The robust solution ensures that the total planning cost is minimized based on the possible variation of the forecasted wind generation within its uncertainty interval. The objective function is subject to nodal load balance constraint (2), uncertainty constraint of wind generation forecast (3), and other network, operational and BESS constraints as can be found in [13].

$$\sum_{i} P_{it} + P_t^W + P_t^B = \sum_{m} PD_{mt} + C_t^W \qquad \forall m, \forall t \tag{2}$$

The nodal load balance constraint (2) ensures that the hourly generated power from dispatchable units and wind generation, plus hourly BESS output power in each bus equals the total hourly load demand at that bus. Subscript $m$ represents the index for buses. $P^w_t$ and $P^B_t$ are the forecasted wind generation and battery output power, respectively. $PD_{mt}$ is the load demand at bus $m$ at time $t$. $C^w_t$ is a positive variable that is added to the nodal load balance constraint to calculate the optimal wind generation curtailment when it is needed. Wind generation is obtained from the forecast and expanded within a range of uncertainty (i.e. a polyhedral uncertainty set). The range of uncertainty is the upper and lower limits that the wind generation forecast is expected to lie within [14].

$$P_t^W = \hat{P}_t^W + \overline{P}_t^W \overline{u}_t - \underline{P}_t^W \underline{u}_t \qquad \forall t \tag{3}$$

$$\sum_{t} (\overline{u}_t + \underline{u}_t) \le \Gamma \tag{4}$$

Considering a polyhedral uncertainty set, the uncertainty of wind generation forecast is modeled in (3) to identify the worst-case solution. $\hat{P}_t^w$ represents the forecasted wind generation. The upper/lower bars in (3) represent the upper/lower limits of the uncertainty range, and $u$ is the binary variable to ensure that the upper and lower limits do not occur at the same time (when $\overline{u}$ is one, $\underline{u}$ should be zero and vice versa). Using (4), the freedom of binary variables associated with wind generation uncertainty is restricted by the uncertainty limit Γ. The uncertainty limit ensures that the wind generation uncertainty cannot exceed a certain limit, which is bounded by restricting the number of hours during which the uncertain forecast can reach either of its bounds. The robustness of the solution can be further controlled by the uncertainty limit to allow application based on risk-aversion. The risk-aversion solutions are considered as conservative, moderate and aggressive. The conservative solution considers larger uncertainty limit and provides a more robust solution against uncertainty. Conservative solution results in large total planning cost with lower risk of unserved energy. On other hand, the total planning cost of the aggressive solution (i.e. smaller uncertainty limit) will be small while the solution is less robust than the conservative solution. The moderate solution considers an uncertainty limit between the conservative and aggressive solutions [14].

## 3. NUMERICAL SIMULATION

The viability of the proposed robust optimization model is tested on IEEE 118-bus test system. A 200 MW wind farm is connected to bus 2, which has two 100 MW transmission lines connected to it. The upper and lower limit of the uncertainty range is considered to be +10% and -10% of the wind generation forecast, respectively. The BESS characteristics are shown in Table 1. The model is solved for two cases with and without considering the wind forecast uncertainty to show the impact on the results.

Table 1. The BESS Characteristics

| Power Rating Capital Cost ($/MW-yr) | Energy Rating Capital Cost ($/MWh-yr) | Depth of Discharge (%) | Efficiency (%) |
|---|---|---|---|
| 20,000 | 11,000 | 80 | 90 |

**Case 1: Ignoring wind generation uncertainty:** In this case, the robust optimization model is solved for a one-year period without considering the wind generation uncertainty. The obtained solution is to curtail a total of 36 MWh of wind generation. The total planning cost is calculated as $225,500,500. The optimal BESS size is found to be 32 MW and 40 MWh for power and energy ratings, respectively.

**Case 2: Considering wind generation uncertainty:** The wind generation uncertainty is considered in the robust optimization model to obtain a more practical solution. In this case, the wind generation curtailment is increased to 43 MWh, i.e., a change of 19.4%. The total planning cost is increased to $225,827,300, showing an increase of 0.15%. This small increase in the cost increases the solution robustness against the wind generation uncertainty. Similarly, the optimal BESS size is increased to 53 MW and 106 MWh for rated power and rated energy, respectively. This is a large increase in BESS size; however, it is required to increase the solution robustness. Figures 3 and 4 compare the results in Cases 1 and 2.

A sensitivity analysis on changing the upper and lower limits of the uncertainty range is studied to determine the impact of the uncertainty range on the wind generation curtailment and the total system planning cost. The range of uncertainty is selected to be 0, ±5%, ±10%, and ±15%. Figure 5 illustrates the impact of changing the uncertainty range. It is clear that the total planning cost is minimum when there is no forecast uncertainty, which means the forecast is 100% accurate; however, this solution is less practical as this error is almost impossible to achieve. When the uncertainty range increases, the solution robustness against the uncertainty is increased which results in a larger total planning cost. The wind generation curtailment is further increased as the forecast uncertainty increases.

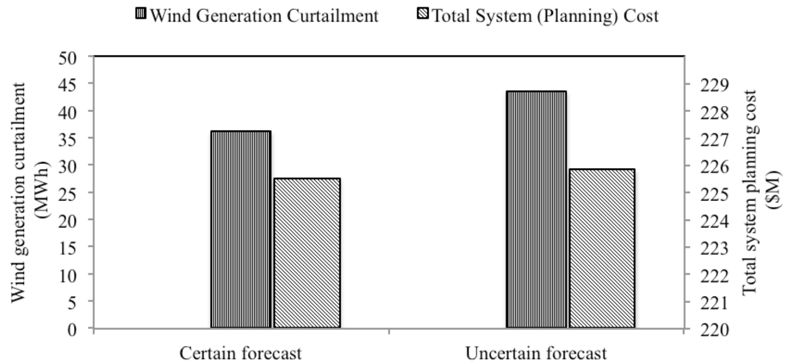


Figure 3. Comparison between Cases 1 and 2 on wind generation curtailment and total planning cost

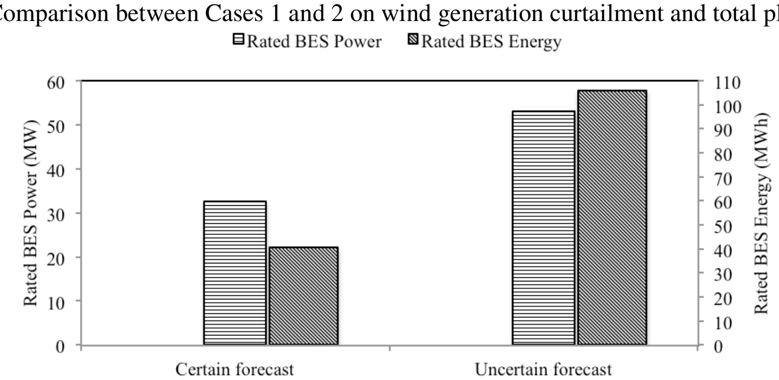


Figure 4. Comparison between Cases 1 and 2 on optimal BESS size

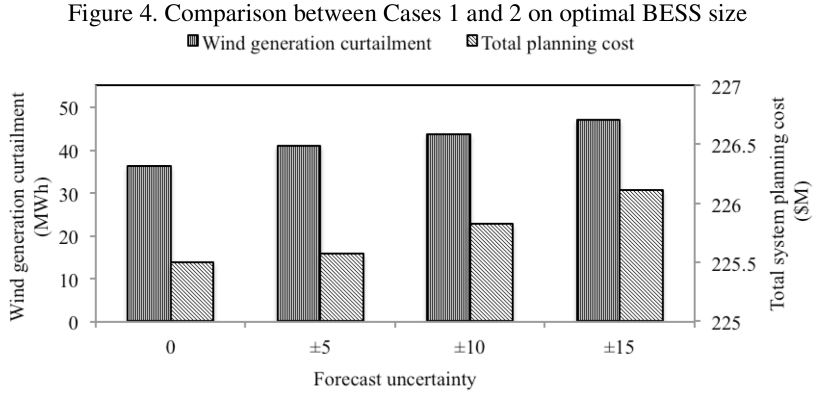


Figure 5. Impact of changing forecast uncertainty

## 4. CONCLUSION

A robust optimization model was proposed and developed in this paper to help reduce wind generation curtailment. The model was capable of determining the worst-case solution under prevailing uncertainty of wind generation forecast. Furthermore, it could efficiently obtain the optimal wind generation curtailment that is required based on transmission network congestion. The model also featured the ability to install the optimal BESS size to optimally reduce the energy waste caused by wind generation curtailment. The proposed model was applied to the standard IEEE 118-bus test system with a wind farm and a BESS connected to a selected bus. The numerical simulations proved the effectiveness of the proposed robust optimization model. Considering the wind generation uncertainty helped to obtain a more robust solution. The total planning cost, wind generation curtailment and the optimal BESS size, however, were increased compared to ignoring uncertainty. Including wind forecast uncertainty in the planning problem provided a more practical solution to avoid further investments in support of existing electricity infrastructure.

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