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Scaling of wind energy variability over space and time

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HIGHLIGHTS

- Quantified the scaling of geographic smoothing effect for wind energy deployment.
- A single wind aggregation will not minimize operational integration costs.
- Minimizing low-frequency output variance results in higher capacity factors.
- Minimizing high-frequency variance needs a larger regional coordination among RTOs.

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ABSTRACT

We use a large data set of simulated wind energy production in the United States to quantify the geographic and temporal scaling of energy output variability reduction when multiple sites are aggregated. We add to the existing literature on “geographic smoothing” by (i) quantifying the scaling of geographic smoothing over multiple spatial and temporal scales; (ii) bounding such smoothing through the use of an algorithm that produces minimum-variance sets of wind energy production sites; and (iii) quantifying inherent tradeoffs in optimizing wind energy site selection to minimize output variability along a specific frequency. The number of wind farms required to minimize output variability increases linearly with spatial scale of aggregation, but the scaling factor is small, on the order of 10^{-6} relative to geographic distances. These scaling factors increase by a factor of two as the frequency considered increases by three orders of magnitude (minutes to months). Our analysis indicates that optimizing wind deployment over one particular frequency increases output variability over other frequencies by nearly 30% in some cases.

1. Introduction

Wind energy is experiencing considerable growth in its penetration in the US power grid. While this growth can bring about several economic and environmental advantages, it comes with a number of system integration challenges. Since wind energy output cannot be predicted perfectly (although predictive abilities are improving and changes in wind energy output over short times scales are generally not extreme [1]), the power system operator needs to hold a portfolio of complementary resources such as capacity markets and ancillary services [2,3], which has the potential to increase the costs of large-scale wind integration. Specifically, in [4], Hoogwijk et al. concluded that as share of wind output in electricity generation mix rises other factors such as increased requirement for back-up power and building wind farms at less suitable locations will cause an increase in overall system costs, and these costs tend to increase as wind penetration increases [5]. Another subject of interest is the incentives for other sources of electricity generation such as thermal power plants when wind power penetration is increasing. For the case of German grid, it has been argued that if the market prices are lowered by more than 5 percent then it would considerably decrease the incentives for investing in new natural gas plants [5].

A number of studies have focused on the smoothing effect from interconnecting wind plants over wide geographic regions to reduce volatility of output, which would directly affect wind integration costs. This aggregation has been encouraged by some power grid operators in the United States through attempts to limit market participation by renewable energy operators that have not aggregated with complementary resources. The research literature is in broad agreement that wind energy production output can be smoothed with sufficiently clever geographic diversity, amounting to interconnecting wind sites with low correlation. Short term variability of wind power can be smoothed even by having a single wind farm that uses only two wind turbines within small distances from each other (about 170 m). However, in order to increase wind power supply reliability over longer time periods a larger

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catchment area is needed. These results can be shown by employing correlation coefficient of power change [6]. Holttinen et al. [7] studied the variability of wind power and reserve requirement using standard deviation as the measuring unit.

Another study found out that by adding more sites to an interconnected queue, correlation among sites become smaller and the reserve requirement for an array of 19 sites will be 47% less than the reserve requirement for a single site [8]. The effect of long distance interconnection on average hourly change in power output have been studied in [9]. They found out that connection of a few wind farms will reduce the average hourly change in output but enlarging the region will not result in considerable reduction of this measure. Further, they concluded that interconnection will increase firm power output.

Gunturu and Schlosser [10] studied the variability of wind power across Independent System Operator (ISO) regions in the US. They incorporated generation duration curves to show that even with aggregation, a large number of hours without wind (or less than 5% capacity) can be observed. Further, by using coefficient of variation they showed that benefits of aggregation vanish quickly after aggregating several wind sites. Rose and Apt used reanalysis datasets to study the variability of wind power [11]. Their results indicated that wind aggregation could significantly reduce the annual coefficient of variation (5–12% for individual wind sites versus 3% for the portfolio). Aggregating windfarms across large regions will reduce the variability of wind power output because correlation between windfarms decreases as distances between sites become larger [12]. Using datasets from three regions (USA, Canada and Australia), the authors calculated the extent of geographic diversity required to make the aggregation effective. Louie [13] performed a statistical analysis of wind aggregation in several RTOs in the US. He found out that the correlation between RTOs are very similar to the correlation between single wind sites. However, the former exhibits larger magnitudes relative to the later. Handschy et al. [14] used 9 windfarms from different regions across the US which results in low correlation between each pair of windfarms. They found out that the number of low power hours will decrease as the number of windfarms increase. This decline has an exponential trend. Huang et al. [15] concentrated on meteorology aspects of wind power. They concluded that by aggregating 5–10 wind farms the high frequency variability can be significantly eliminated. Authors in [16] used Monte Carlo simulations to determine the number of effective generators that provide firm capacity. Apt [17] uses the power spectral density of wind sites to study different types of fill-in power that can efficiently compensate for variations in wind power.

Other studies have focused on investigating the benefits of hybrid renewable systems. Suomalainen et al. [18] studied the correlation of hydro and wind resources with electricity demand and prices. Their analyses showed that using wind sites that have negative correlations with hydro resources, could reduce high price fluctuations in hydro-dominant electricity systems. Further, they found out that both the spatial and temporal distribution of wind resources should be analyzed in order to create a combined wind-hydro system that maximizes the correlation between supply and demand. Hirth [19] incorporated a numerical model to show that in hydro-dominant electricity systems, the drop in wind value is much smaller compared to systems without hydro power. He concluded that flexibility of hydro power benefits wind aggregation. By studying high penetration of wind and solar in the electricity system of Croatia [20], authors found an optimal mix of renewable generation technologies that would reduce electricity import and lower CO_2 emissions. Further, a number of papers have identified other measures of facilitating wind integration into the grid by coordinating generation and expansion planning [21] and improving forecast capabilities [22].

While this large body of research has articulated the potential benefits in variability reduction from geographic aggregation of wind energy, there has been no settlement on a best-case magnitude of that variability reduction, and very little discussion of best-case aggregation scenarios over different spatial and temporal scales. We add these missing pieces to the existing body of literature by using a large public data set of simulated wind energy production to examine the smoothing of wind power output through aggregation across spatial scales from thousands to millions of square kilometers. We perform a best-case bounding assessment of the potential for geographic smoothing and to understand quantitatively how geographic smoothing scales over multiple spatial and temporal scales. Our best-case approach introduces a variance minimizing algorithm that sequentially connects wind farms based on the variance of their joint power output, yielding an evolution of wind energy penetration that is consistent with best-case output variance minimization.

Consistent with previous research [9,10], we find that geographic aggregation of wind energy does reduce output variability, but only to a point. While other studies [7,9,10,12,13,15,17] have focused on finding the efficient number of wind sites or the geographic scope to minimize the wind output volatility or increase firm power output by considering available wind site locations, we have proposed a systematic method to find wind site locations that achieve the same goals. Unlike previous work, we do not consider the location of wind sites as already given; our analysis, rather, is intended to describe the location of wind build-out over space in order to achieve best-case variability reduction over several temporal scales. Although this study provides a valuable statistical characterization of wind aggregation over various spatial and temporal scales, the actual deployment path of wind farms in the developed world is likely to be different, since minimizing output variance is not the same objective as maximizing profits or wind energy output. As such, our critical contributions to the existing body of work on geographic smoothing of wind energy are : (1) minimizing wind output variability over low frequency time scales will yield higher capacity factors and higher wind output than optimizing wind site selection to minimize output variability over higher frequency time scales; (2) optimizing wind farm deployment to achieve output variance minimization over one-time scale does not imply minimizing output variance over other time scales; (3) quantification of the inter-temporal tradeoffs associated with building wind energy capacity to maximize aggregation benefits at a specific time scale (for example, we find that building out wind energy capacity to minimize hourly output variance actually increases output variance at slower frequencies); (4) the number of wind farms required to achieve minimum output volatility grows with spatial scale of aggregation, but the scaling factor is small relative to geographic scale; and (5) minimizing wind output volatility over different time scales requires different siting criteria.

The main study area we use covers the US Eastern Interconnect (basically the area of the North America power grid east of the Rocky Mountains) and includes more than 1300 simulated windfarms, with data taken from the NREL Eastern Wind Interconnection and Transmission Study [23]. The existing literature [24] points out that this data set tends to under-estimate power output variability at shorter time scales, i.e., sub-hourly. This does not qualitatively affect our conclusions since we observe less variability over longer time scales. In this dataset, wind power generation is available for 1326 simulated wind farms. These wind farms are shown in Fig. 1. The data is available in 10-min interval format for a period of three years from January 2004 to December 2006; therefore, each wind farm is described by a vector with 157,824 elements. These wind sites have different capacities; therefore, we have normalized the wind generation data by dividing each