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Diversifying wind power in real power systems

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ABSTRACT

One method to reduce wind variability is to diversify the wind power resource by interconnecting wind resources across a larger geography. This study uses a modified version of mean-variance portfolio optimization (MVP) to assess the potential for diverse wind to reduce the variability of wind. A one year unit commitment and economic dispatch model of the U.S. Midwest is used to understand the value of the reduced variability. The model assesses four different wind portfolios, ranging in diversity, of two wind power penetrations (10% of total system load and 20%). Employing MVP, the variance in the ramp rates decrease by 50% with a 4% increase in capacity in the 20% wind penetration and a 2% increase in the 10% penetration. With a 20% wind penetration, decreasing the ramp rate variance can reduce curtailment from 5% to 0.1%. In the absence of significant curtailment, decreasing the ramp rate variance reduces the proportion of conventional generation required for ramping. However, the impact on total production cost and emissions from conventional generation is complicated by complexities of the power system, including transmission constraints and the time of day of ramping.

1. Introduction

Wind power variability is one of the pressing challenges in integrating large quantities of wind into the grid. The fast ramping up or down of wind power can have negative consequences on grid operations, including increased costs, inefficient operation of conventional generators, and the need for additional ancillary services [10,11,16]. One method to deal with the variability of power output from individual wind farms is to develop and interconnect other wind farms that are subject to different wind patterns, diversifying the wind power portfolio. If proper wind power portfolios are chosen, the cumulative power output of the portfolio will be smoother relative to the output from individual wind farms. However, reduced variability through wind portfolio diversification may require the development of lower quality wind sites, resulting in a tradeoff between output variability and the average power output of the entire portfolio. Wind diversification also spreads the wind farms out geographically, potentially reducing the need for extensive transmission capacity expansion in the regions of highest quality wind (high capacity factors). However, transmission congestion across the region spanned by the wind farms reduces the ability of the wind farms to counteract each other's variability. The goals of this research are to (1) further investigate optimization techniques used to examine diverse wind, and (2) offer a new understanding of the impact of diverse wind on the power system.

1.1. Optimizing diverse wind power

To evaluate the impact of wind diversity, this study implements a modified version of the multi-objective optimization method called Mean-Variance Portfolio optimization (MVP). The two objectives of MVP are to minimize the variance of the cumulative power output ramps, called the ramp rate variance in this study, and to maximize the average cumulative power output of the wind farms. The power output ramps are defined as the change of the cumulative wind power output from a point in time to the next. The ramp rate variance is non-linear and requires quadratic programing to minimize, while average power output is linear. The decision variables for the multi-objective optimization problem are the size of the possible wind farm sites, which includes the option to not building at a site.

MVP has been used before to analyze wind power diversity Hansen [6]. Investigated its use to provide additional capacity credit for interconnected wind farms. Examining three wind farms Hansen [6], used MVP to minimize the deviation from average output

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given the objective of increased capacity credit, rather than decreased wind power variability.

Degeih and Singh [2] also optimized the siting of wind farms using MVP. Similar to Hansen [6]; the study minimized the deviation from the mean output. Using wind sites from the National Renewable Energy Laboratory (NREL) wind dataset [19], the optimal portfolios were evaluated using loss of load probability (LOLP) to determine the capacity credit of a wind portfolio with reduced variability.

Roques et al. [28] applied MVP to find optimal wind power portfolios across Spain, France, Germany, Denmark, and Austria. Two methods were used: one minimized wind ramping variability and another minimized variance from the average output during peak hours. In all cases, the study found that the existing wind power portfolio and projected portfolios could achieve significant reductions in variability at the same power output by using MVP to better plan wind projects. Although the authors considered cross border transmission constraints and inter-country wind resource potential, their treatment did not account for other sources of power also using the transmission lines to deliver power from one country to the next.

Rombauts et al. [27] further explored the issue of transmission capacity constraints when using MVP to determine efficient wind farm build out. While they tackled the issue of transmission in greater depth than Roques et al. [28]; the optimization model still limits the use of the transmission capacity to wind. Unlike the earlier studies Rombauts et al. [27], chose wind sites to minimize ramp rate variability rather than the deviation from the average.

Other studies also investigated wind power diversity without the use of MVP. Some studies used other mathematical approaches, such as robust optimization, sequential optimization, and point estimate methods, to create diverse wind buildouts [14,25,26]. Other studies investigated the benefits of diverse wind and its economic impact [9,10,29]. Also, diversity from renewable energy sources is not limited to wind. Studies have investigated diversity benefits from geographically dispersed solar [17] and the co-location of wind and wave energy [30].

This study builds on past work using MVP to analyze wind diversity. The major differences with past work include the focus on minimizing the wind power portfolio's ramp rate variance rather than minimizing its deviation from the average, the restructuring of the MVP framework to meet an annual wind energy target (wind penetration level) rather than a fixed wind power capacity, and employing a power systems model to assess the value of wind diversity. The power system model will be discussed in the following section.

Similar to Rombauts et al. [27]; this study minimizes ramp rate variability of the overall portfolio. Most past studies minimize the deviation from the average power output. To reduce system ramping requirements, it is important to decrease the magnitude and frequency of large ramps (up or down) in the wind power output. This will generally minimize the negative system impacts of wind power variability, which is not necessarily true when minimizing the deviation from the portfolio's average output. Minimizing the deviation from the average also penalizes portfolios with periods of high power output. Typical average power output from wind farms range from 35 to 45% [19]. In hours when the portfolio operates close to 100% of its capacity, the power output variance increases, thereby penalizing the portfolio when the objective is to minimize deviation from the average. Instead, by minimizing the ramp rate variance the portfolio is not penalized for operating well above its average power output, as long as the change in output is gradual.

To assess the impact of diversification in the power system, this study creates portfolios using MVP that have constant total annual wind energy output for each portfolio. This is unlike other MVP studies which maintain constant wind power capacity for each portfolio. Constant energy allows for a better comparison of results from the unit commitment and economic dispatch (UCED) model. It also is analogous to Renewable Portfolio Standard (RPS) policies established in many states in the United States, which require that electric utilities meet a particular percentage of their retail sales (load) with renewable energy. To do this, the decision variables of the modified framework have units of installed capacity, rather than the share of capacity a wind farm contributes to the overall portfolio.

1.2. Modeling diverse wind in the power system

This study will build on the wind diversity research to date by analyzing how different levels of wind diversity impact the operations of a real power system. Multiple studies have used power system models to quantify impacts of integrating variable renewables into the grid. Some of these studies used such models to better understand the impact and efficacy of renewable energy policies [1,24,31], while others focused on operational changes and the emissions implications of the integration of wind power [5,13,15,34,23,32]. However, neither these studies nor the studies focused on wind diversity model the impacts of resource diversification on power system behavior, as this study proposes.

After using MVP to create different wind power portfolios, ranging in level of diversity, this study quantifies the ramping impacts the different portfolios induce on the power system. For this part of the study, we use a UCED model to determine the power system's response to different wind portfolios.

This study also investigates how transmission constraints impact diverse wind portfolio's ability to decrease system ramping. MVP does not capture transmission constraints, but geographically diverse wind can reduce wind power curtailment induced by transmission congestion. Also, MVP assumes the variability of one wind farm can be counteracted by any combination of wind farms that have equal variability in the opposite direction. However, if the transmission within the region is congested, either from wind power or other sources, the variability will not be offset.

2. Methods

This study employs MVP and power systems modeling to analyze the value of diverse wind to reduce wind power variability and how the reduced variability impacts the rest of the system. MVP is first used to develop a set of wind power portfolios, ranging from portfolios heavily concentrated in regions with high quality wind to portfolios widely spread across the considered region. The different wind power portfolios are then evaluated using a UCED model to measure the power system's response to the integration of the different wind power portfolios. This power systems model is first run assuming no transmission constraints (i.e., “copper sheet”), and then again with inter-zonal transmission constraints enforced. This isolates the impact of MVP's inability to capture transmission constraints and helps clarify the actual ability of wind diversity to decrease the system impacts of wind variability in a real system.

2.1. Optimizing diverse wind portfolios

The two objectives of this application for MVP are to (1) Minimize the installed capacity of wind power, and (2) Minimize the ramp rate variability from a point in time to the next (this study considers 10-minute time intervals). The first objective (equation (1)),