The capacity value of optimal wind and solar portfolios

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Abstract

Using large data sets of simulated wind and solar energy production, we create optimal wind, solar and blended (combined wind and solar) portfolios over various spatial and temporal scales, and use portfolio theory to quantify the capacity benefits in various portions of the electric grid in the Eastern United States. We add to the existing literature on portfolio analysis of renewable energy resources by (i) studying the benefits of optimal aggregation over various spatial and temporal scales, (ii) quantifying the capacity benefits of renewable portfolios over space and time, and (iii) analyzing spatial distributions of renewable installations in optimal renewable portfolios. The results indicate that full time availability of wind and blended portfolios are respectively 14 and 17 times larger than full time availability of an individual wind farm and adding solar to wind portfolios increases the availability factor of renewable portfolios by more than 40% in most regions. Further, optimal hourly portfolios provide higher capacity value relative to daily and weekly portfolios.

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1. Introduction

As the penetration of weather-dependent renewable energy resources in electric power grids increases, system operators need to accommodate this variable and forecast-dependent supply while maintaining the reliability of the bulk power grid. Installed capacity requirements are one mechanism to maintain the adequacy of power generation resources to meet anticipated peak-level demands. These installed capacity requirements are met variously through targeted utility investments or through market mechanisms. Because the output of renewables such as wind, solar and run-of-river hydroelectric vary over both space and time, measuring the contribution of renewables to system capacity requirements is not always straightforward. Previous work has shown that employing renewable power over a diverse geographic area tends to decrease output variability [1–7], but such wide-area aggregation involves tradeoffs in power output volatility over both time and space [4]. In contrast to prior research, the present paper does not focus solely on minimizing power output volatility from wide-area aggregation of renewable power supplies, but explores mean-variance trade-offs by minimizing variance for different values of generation output (portfolio return). We find that there is no single optimal portfolio that can minimize risk, for a given level of return, simultaneously over multiple temporal and/or spatial scales.

This work uses large public data sets of simulated wind and solar production in North America and Mean-Variance Portfolio theory (MVP) to examine the composition of optimal wind and solar portfolios (i.e., the sets of wind and solar investments where higher output levels cannot be achieved without a corresponding increase in output volatility). We illustrate how these optimal portfolios vary over space and time across the United States, and illustrate how MVP theory can be used to determine benchmark capacity values for aggregated portfolios of wind and solar power.

MVP theory has been widely used in finance to create sets of efficient portfolios with maximum return for any level of risk. This method is also known as the portfolio optimization approach. During the past decade, several papers have used portfolio optimization to create efficient mixes of generation assets in the electricity market. Awerbuch showed that adding renewables to the electricity generation portfolio (i.e. diversification of the portfolio) reduces generation cost and increases energy security [8]. Our findings further support Awerbuch’s results regarding benefits of a diversified portfolio; adding solar to wind portfolios reduces portfolio risk and likely decrease renewable integration cost. In another paper, Awerbuch and Yang produced efficient power generation capacity portfolios for the European Union that

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https://doi.org/10.1016/j.energy.2017.12.121
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maximize energy security and address the climate-change impacts of electric power generation [9]. Delarue et al. [10], considered a model that is capable of considering the difference between power and energy and therefore allowing for non-dispatchable sources such as wind. In another study [11], the portfolio approach has been used to model allocation of electricity generation into bilateral contracts and spot markets. MVP has been used in Ref. [12] to create long-range scenarios for the Dutch electricity generation mix. The results of this study show up to 20% risk reduction which in part is due to promotion of renewable electricity generation. The MVP approach has also been used to analyze impacts of technology cost on energy portfolios. For example, Costa et al. [13] investigated how uncertainty in cost parameters of various technologies and the interactions of these cost parameters could impact optimal energy portfolios. This essentially shows the importance of portfolio theory; technologies should not be evaluated separately as their interactions have significant impacts on portfolio risk and return (also emphasized in Refs. [8,9]). This is an important aspect of our study too; we calculate portfolio risk by considering the interactions between different wind and solar installations (i.e., the covariance matrix). Many other energy models are not capable of considering these interactions [6].

Other papers have also used MVP to show the advantages of diversification in the electricity generation portfolio [14–16]. Arnesano et al. [14], as with [6,8] concluded that the addition of renewable energy sources to the generation portfolio would reduce system risk. Other studies have focused on analyzing effects of diversification on wind generation. Dispersing wind farms over a large region tends to reduce wind output volatility for a given level of wind generation. This was confirmed in a case study in the UK [6] which investigated the benefits of dispersing 2.7 GW of capacity among four wind sites versus installing the same capacity at a single location. While this paper is one of the first studies using portfolio theory to show the benefits of aggregation in reducing wind power volatility, it does not consider different spatial and/or temporal scales and it only includes four wind farms in the UK. In another study, Roques et al. created optimal wind generation portfolios across several European countries by using modern portfolio theory [17]. In this study, impacts of transmission and resource constraints on efficient portfolios have been analyzed. Their study covers a larger geographic area (compared to [6]) with higher geographic diversity but still fails to consider the impacts of spatial and temporal variability on optimal portfolios. Possible advantages of wind generation in optimal portfolios in Ireland have been studied in Ref. [18]. The authors showed that enforcing high taxes on carbon emissions could increase wind power share up to 20% (for low fuel prices) or 30% (for high fuel prices) percent of the generation portfolio. Matos et al. used the same method to create optimal renewable portfolios in Portugal [19]. Novacheck and Johnson used MVP to show that wind portfolios can reduce the ramp rate variance and decrease wind curtailment [20]. Santos-Alamillos et al. evaluated different repowering scenarios of current wind farms by using MVP theory [21], showing that repowering can reduce portfolio risk while maintaining a given level of portfolio return.

Other papers have focused on studying the benefits of aggregating renewable resources such as increasing the amount of firm power, reducing the annual coefficient of variation, and reducing the number of low power hours [1–3,22–29]. Aggregation of multiple types of renewable power generation technologies have also been assessed, including wind and wave power, wind and solar power, and wind, water, and solar power. Stoutenburg et al. used buoy data from California to analyze the reduction in output variability of wind and wave power when they are aggregated [30]. Thomaidis et al. studied the benefits of combining wind and solar resources in optimal energy portfolios. They found out that by adding solar power plants to portfolios of wind farms, we can reduce the volatility of wind portfolios [31]. Neto et al. [32] used portfolio theory to study portfolios of renewable resources. Their study adds to the existing literature on mean-variance portfolio theory by studying shares of wind, solar and hydro in optimal renewable portfolios. As with these prior works [31,32], our analysis suggests some benefit of aggregating wind and solar power in a single portfolio. Our study goes further than previous studies [6,17,19,21,31,32], however, in the use of MVP theory to define optimal portfolios and to identify the impacts of spatial and temporal scales on the quality of portfolios assembled via MVP type methods. A more limited number of analyses [33] have also examined how technology diversification through the coupling of wind and solar power can reduce aggregate power output forecast errors.

While this large body of research has expressed the benefits and limitations of aggregating renewable resources, there has been no study, to our knowledge, considering optimal renewable portfolios over different spatial and temporal scales. There has also been little focus on comparing optimal portfolios based on different measures such as return/risk ratio or geographic diversity. Finally, no previous study has focused on how the spatial distribution of various renewable portfolios are different based on the frequency of analysis, spatial scale of aggregation, or renewable technology. In this paper, we address these gaps in the existing literature by incorporating Mean-Variance Portfolio (MVP) theory to study wind and solar power aggregation over multiple spatial and temporal scales. Our objective is to analyze how spatial and temporal scales influence optimal wind and solar portfolios. We use the NREL Eastern Wind Interconnection and Transmission Study dataset [34] which includes more than 1300 simulated windfarms, and NREL’s Solar Power Data for Integration Studies [35] which includes more than 4000 solar photovoltaic power plants in the US Eastern Interconnection. We have used these datasets to create: 1) optimal wind portfolios, 2) optimal solar portfolios, and 3) optimal blended (wind and solar) portfolios.

In order to study the effects of spatial scale on optimal portfolios, we have categorized wind and solar farms into different groups based on their region. The regions in our study are the regional transmission organizations (RTOs). Fig. 1 shows the map of RTOs in the Eastern United States. Note that SERC and FRCC are regional electric reliability councils, but jointly they share similar geographic reach as many RTOs. In this study, we combine SERC and FRCC into an analysis unit called SE-FR. We also use the term “RTO” somewhat loosely in this paper to refer to an actual RTO.

![Fig. 1. Map of the regional transmission organizations (RTOs) in the US Eastern Interconnect.](image-url)
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