MITIGATION OF WIND FARM OUTPUT VARIABILITY VIA GEOGRAPHIC DISPERSION AND TURBINE DIVERSIFICATION: A MEAN-VARIANCE ECONOMIC MODEL

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Overview

Wind is a reliable source of energy for the long-term. However, its intermittent nature results in high variations in the power outputs of wind turbines, thereby posing the biggest challenge in wind farms' successful integration to power grids. Wind speeds exhibit a spatially weakening correlation, which could be exploited to mitigate the such variations at the macro scale. However, the current practice in wind energy evaluation and investment is such that candidate wind farm sites and turbines are evaluated individually, with the goal of determining the "optimal" site-turbine combination that maximizes the average output (or profit) return on the investment. While certain reliability considerations may be taken into account, an insufficient degree of attention is paid to minimizing the overall output variability that will result from the chosen site-turbine configuration. Such lack of industry/government consciousness about the cruciality of wind energy risk assessment also leads to reckoning without the possibility to reduce such risks via geographical dispersion of the farm and diversification of the wind turbines used. Our study aims to offer a simple general model to show how significant a reduction in total wind power can be achieved by a smart choice of geographically dispersed sites and also by the use of several different turbine models across and, more unconventionally, within these sites.

Method

Borrowing ideas from the mean-variance portfolio theory in finance and using optimization tools, we develop a mean-variance model of optimal site and turbine selection for an investor that wishes to achieve a target power output rate per dollar of investment (including future costs of operating, maintenance, etc.) with the minimum possible variance of this rate of return over the life of the investment. Due to the intra-annual seasonality of wind speeds in a typical location (yielding a "systematic" annual variance) , we consider the intra-day variance as a more meaningful measure of risk, thereby defining a modified objective of minimizing the average daily variance. Unlike existing models in the literature, our model adopts a bottom-up approach via a fully endogenous specification of which sites and what turbines to use. The resulting mathematical programming model is a quadratic program with linear constraints. The goal is to determine the set of efficient solutions (termed "Pareto optimal" in economics or "efficient frontier" in finance) that correspond to different levels of the target power per investment. This continuous frontier is approximately traced by solving the mathematical model for discrete increments of the target power per investment parameter over its appropriate range. The numerical model is developed with the GAMS software and solutions are obtained by the PATHNLP and CPLEX solvers.

Results

The significance of the results depend strongly on the time resolution of the wind speed data, the length of the time-series, the adequacy of the measurement heights, and the geographical dispersion of the measurement sites. Among publicly available such data, the National Renewable Energy Laboratory's (NREL) *Eastern Wind Integration and Transmission Study* (EWITS) study, which involves 10-minute instantaneous measurements for the years (2004-2006) taken at 80 and 100 meters at several locations in each of the many eastern states of the U.S., offers these desirable qualities. A case study is performed using the wind speed data for the year 2006 from a total of 140 sites dispersed across the neighboring states of Indiana and Illinois. Eight different types (size- and model-wise) of Vestas turbines, ranging from 850 kW to 3 MW capacities, are considered. Data pertaining to the turbines' power curves are obtained from the manufacturer's brochures and the *Swiss Wind Power Data* website. Two-piece polynomials are fitted to the power data, yielding a more realistic power curve as compared to the commonly adopted simple cubic form. Regarding the ever-elusive accurate cost data, we use the average figures from the *2011 Wind Technologies Market Report* published by the U.S. Department of Energy. The numerically-approximated efficient frontier indicates that considerable reduction in average daily variance (roughly 25% reduction in its square-root) can be achieved by an optimal selection of dispersed wind farm sites and a few best-suited turbine models. The optimal budget shares of site-turbine combinations vary along the efficient frontier. A particularly important outcome is that not all sites and all turbine models are included in the efficient solutions. Only 3 out of the 8 turbine models considered are ever selected for the sites and, also, 102 out of the total 140 sites are ever selected. Moreover, most of the efficient sites involve only 1 turbine model, a lesser number involves 2 different turbines, and an even lesser number involve 3 turbines. It is also noteworthy that the sites chosen by the model are relatively dispersed across the geography, where sites having more than one turbine type assigned are especially positioned along the perimeter of the area.

Conclusions

Spatial and turbine-based diversification of wind farm investments (i.e. geographic dispersion of turbines over several distant sites and the use of several different turbine models across and within the sites) can provide considerable reduction in the variability of the total power output (as compared to concentrating the entire investment on a single site and single turbine model). Our case study involving a rather arbitrarily chosen geographic area (which happens to have a relatively flat terrain and thus high spatial correlation of wind speeds) successfully demonstrates this possibility. With a more careful selection of the geographical region (which requires more data analysis) and many more turbine models (especially low-wind turbines with smaller rated powers), this reduction can be much more substantial. The case study also suggests that turbine-model diversification is more beneficial only together with geographic dispersion, but not so much within a given site. Despite its limited scope and simplifying assumptions, the model offers as a general framework for analyzing the site- and turbine- diversification gains with other possible measures of risk (e.g. VaR), other objectives (e.g. profit maximization instead of a power-yield target), and other more realistic technical constraints and parameters.

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