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Innovative Applications of O.R.

A portfolio model for siting offshore wind farms with economic and environmental objectives

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A B S T R A C T

Siting offshore wind farms is a complex problem due to the wake interactions between wind farms. We develop a profit maximizing portfolio model based on underlying network models to track the wake effects through a series of wind farms. Our portfolio model optimizes the siting of wind farms considering multiple wind directions and wind speeds and performs better than simple decision heuristics. Excluding sites from the portfolio has nonlinear impacts on the profitability of the portfolio of sites in that areas excluded from consideration have greater impacts on profit if they are grouped together or aligned parallel to the prevailing wind direction. The model can be readily adapted to include additional cost factors.

1. Introduction

Generating electricity from offshore wind farms can help coastal regions meet growing electricity demands from renewable sources. There are many demands, however, on the offshore space from recreational, commercial, and conservation uses. This paper builds an optimization framework to address two challenges present in planning for siting offshore wind farms: 1) how to plan for a potentially large number of offshore wind farms in the presence of wake interactions at the wind farm level, and 2) how to account for the costs of excluding sites from the choice set for development due to competing demands.

Existing uses can preclude a significant portion of the wind resource from wind farm development (Sheridan, Baker, Pearre, Firestone, & Kempton, 2012). The U.S. National Renewable Energy Lab (NREL) set a target of 86 gigawatts of offshore wind in the U.S. in their Wind Vision Study (U.S. Department of Energy, 2014). Depending on the density of wind turbines, meeting this goal will require developing about 10% of the currently feasible Federal offshore waters off the Atlantic coast (Schwartz, Heimiller, Haymes, & Musial, 2010).

We focus on optimizing the siting of wind farms since, once installed, the location of a wind farm cannot be adjusted, only its operation (Singh, Baker, & Lackner, 2015). A large portion of the costs related to offshore wind energy occurs during installation, which means that operators want to maximize operating time over the life of the facility and avoid unanticipated curtailment or reduction in efficiency.

As offshore wind farm development grows, so does the potential for interactions between individual wind farms, as well as for cumulative environmental impacts to the surrounding ecosystems. While individual wind farms generally have negligible population level impacts to the surrounding ecosystems, hundreds of wind farms could result in an accumulation of impacts larger than the sum of the individual impacts (Berkenhagen et al., 2010). Large scale wind farm development could lead to tipping points such as cumulative collision mortality rates which reduce a species' long run population or habitat fragmentation caused by wind farms acting as a barrier to movement between essential habitats (Drewitt & Langston, 2006; Hüppop, Dierschke, Exo, Fredrich, & Hill, 2006). Due to the non-linear interactions among wind farm sites in power generation and cumulative environmental impacts, examination of facility siting policies on a larger scale can illuminate improved pathways for large-scale wind farm development. The alternative – considering wind farm siting as a series of independent decisions – cannot properly address the long-term, interdependent nature of these decisions and could result in suboptimal wind farm development with regard to one or more of the objectives. Developing a

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quantitative understanding of how these interactions develop can aid stakeholders in planning for long term renewable energy targets and environmental conservation goals. Thus, we argue that the problem of wind farm siting should be framed as a portfolio problem, evaluating multiple sites simultaneously.

In this context, we address this problem by developing a top-down optimization model that maximizes the economic value of a portfolio of offshore wind farms while respecting environmental constraints. We use a portfolio approach to examine a set of potential offshore wind farm locations collectively instead of individually, and use this model to examine the tradeoffs between economic and environmental outcomes in this spatial multi-criteria problem.

This research differs in two key ways from previous research. First, we focus on siting multi-turbine wind farms, rather than the layout of individual turbines within farms. The wind farm unit is the appropriate unit for a social planner to consider. Existing models of turbine layout are far too computationally complex to be tractable on the order we are considering if each turbine is modeled individually. On the other hand, wind farms cannot be correctly modeled as single large turbines of equivalent capacity, since the wake resulting from a wind farm is larger and more spread out. Therefore, existing turbine layout models cannot be easily adapted to site wind farms.

Second, we develop a novel modeling approach for capturing the spatial interactions of the offshore wind resource. This approach is based on using linear network models to track how the location-specific wind speeds develop as the wind travels through a combination (i.e. a portfolio) of wind farms. By using these networks for all wind scenarios (i.e., free wind speed and direction), we obtain a linear programming formulation for the power generated by an arbitrary portfolio of farms. Moreover, the linearity of the model is preserved when the wind farms to be developed are treated as decision variables. Thus efficient mixed-integer linear programming (MILP) algorithms can be used to identify a portfolio of wind farms that maximizes economic value while satisfying relevant environmental constraints.

The vast majority of the literature focuses on project developers and prescribes the precise location and arrangement of individual wind turbines within farms, what is called micro-siting. This work typically focuses on maximizing power output for a fixed number of turbines. Due to the complexities of fluid flow within a wind farm, virtually all micro-siting models use heuristic approaches to optimize turbine placement (Elkinton, Manwell, & McGowan, 2008; Lackner & Elkinton, 2007; Veeramachaneni, Wagner, O'Reilly, & Neumann, 2012; see González, Payán, Santos, & González-Longatt, 2014 for a review). Recent work using swarm optimization and genetic algorithms provides additional value in micro-siting problems by removing the requirement to site turbines on a grid (Wan, Wang, Yang, Gu, & Zhang, 2012).

Our work, in contrast, is aimed at regulators and policy-makers, and is intended to inform strategic policy and regulatory decisions related to defining wind energy areas and permitting individual wind farms. This aim has important implications for the modeling choices made in this paper. First, the spatial units of analysis used by the U.S. Federal regulatory agencies are gridded points known as blocks or aliquots (we call them sites). Hence, for each of these sites we consider the binary decision of whether or not a wind farm should be developed, rather than treating the coordinates of each wind farm as continuous decision variables. Second, making informed policy decisions requires an equitable treatment of all available decision alternatives. Indeed, our model can be solved with exact MILP algorithms to identify the true global optimal solution among all feasible ones. Heuristics, in turn, would offer no guarantees that the produced solution is the true optimum. In principle, existing simulation models could be used to evaluate the economic values of each possible site combination. However, as the number of combinations increases exponentially in the number of sites, this approach quickly becomes infeasible: For instance, with a relatively modest grid consisting of 10×10 sites, the number of combinations to simulate would be in the magnitude of $2^{100} \approx 10^{30}$.

A few papers have developed mixed-integer linear programs (MILPs) maximizing power in packing-type problems (Archer, Nates, Donovan, & Waterer, 2011; Fischetti & Monaci, 2016; Turner, Romero, Zhang, Amon, & Chan, 2014; Zhang, Romero, Beck, & Amon, 2014). Fischetti and Monaci (2016) consider the context of a large offshore wind farm and combine heuristics with a MILP formulation. Our approach diverges from this previous optimization work as well as from that of Volker, Hahmann, Badger, and Jorgensen (2017) by focusing not on maximizing power output, but on maximizing the profitability of the wind farms. An increase in power output must be evaluated against the additional capital investment required.

Others have taken a portfolio approach to planning wind farms with agents responding to a market for electricity (Le Cadre, Papavasiliou, & Smeers, 2015). Our approach differs in informing the extensive permitting process that is typical for offshore wind farms, and focuses on ex-ante spatial concerns rather than ex-post market concerns. We take the perspective of the social planner, rather than the agents producing and selling energy, since planners and regulators identify development areas for offshore wind projects in the U.S. Our paper can be seen as a complement to this paper.

We take a novel approach to modeling the spatial interactions between discrete wind farm sites in a portfolio decision framework. The sites are discrete by the nature of the policy. For example, each wind energy area (WEA) in the U.S. is composed of Federal lease blocks, which discretize the offshore space designated for leasing. We develop a network model within the optimization to track how siting decisions impact power generation at downwind farms. This allows us to linearize nonlinear relationships for a discretized space and solve large problems quickly. It incorporates the variability in wind by modeling the frequency over a set of wind scenarios with different wind speeds and wind directions (Baker & Solak, 2011; Liesio & Salo, 2012; Liesio, Mild, & Salo, 2008). The model is computationally attractive because it is a MILP model which can be readily solved for problem sizes relevant to practical problems.

This paper also contributes to the Portfolio Decision Analysis (PDA) literature. Specifically, PDA refers to the theory, methods and practices which seek to help decision makers make informed *multiple* selections from a discrete set of alternatives (for an overview see, e.g., Salo, Keisler, & Morton, 2011). Indeed, the approach developed here demonstrates how complex spatial interactions and uncertainties can be efficiently captured in a portfolio model of practical relevance. In line with PDA literature, we use the term 'portfolio' to refer to a combination of decisions on whether or not a wind farm is developed on each site. It is worth highlighting that financial portfolio models (e.g., Markowitz, 1952) which seek to balance return and risks through diversification have a different purpose: In these models, portfolio refers to the allocation among different (market traded) financial assets.

The remainder of this paper is organized as follows. Section 2 develops the model for optimizing the arrangement of wind farms. Section 3 presents an application using wind data from the Gulf of Maine and explores the effect of restricting environmental corridors from wind farm development. Section 4 shows how the model can be extended to capture wind dynamics through a more precise model. Section 5 discusses the insights that the model can provide for public officials responsible for reviewing offshore wind farm permit applications