Energy Conversion and Management 77 (2014) 484–494

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A system-level cost-of-energy wind farm layout optimization with landowner modeling

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ARTICLE INFO

Article history:
Received 16 March 2013
Accepted 1 October 2013

Keywords:
Wind farm layout optimization
Cost-of-energy
Landowners
Remittance fees
Technology acceptance

ABSTRACT

This work applies an enhanced levelized wind farm cost model, including landowner remittance fees, to determine optimal turbine placements under three landowner participation scenarios and two land-plot shapes. Instead of assuming a continuous piece of land is available for the wind farm construction, as in most layout optimizations, the problem formulation represents landowner participation scenarios as a binary string variable, along with the number of turbines. The cost parameters and model are a combination of models from the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory, and Windustry. The system-level cost-of-energy (COE) optimization model is also tested under two land-plot shapes: equally-sized square land plots and unequal rectangle land plots. The optimal COEs results are compared to actual COE data and found to be realistic. The results show that landowner remittances account for approximately 10% of farm operating costs across all cases. Irregular land-plot shapes are easily handled by the model. We find that larger land plots do not necessarily receive higher remittance fees. The model can help site developers identify the most crucial land plots for project success and the optimal positions of turbines, with realistic estimates of costs and profitability.

1. Introduction

Consider the challenge that wind farm developers face: they must plan a layout for a wind farm with limited information on many important factors, such as wind resource, geology (for tower foundations), and zoning; yet, they only can collect some of this information through a full and costly site survey, which can only be performed once landowners have given them full access to their land and the project is demonstrated to be viable [1]. Thus, developers tend to wait until later in the development process to pinpoint turbine locations, when they have sufficient information, budget, and land access to do so. Yet, developers, landowners, and community members all have an interest in establishing important details of a wind project at an early stage, such as placement of turbines. Here, we investigate another such important detail: determining the land plots most crucial to the success of a wind farm and the costs of leasing this land.

To transform wind power to electrical power efficiently, the placement of wind turbines in a wind farm is optimized to maximize capture of wind resource and minimize wake loss and turbulence interactions from multiple turbines [2]. Wind Farm Layout Optimization (WFLO) research has addressed these conflicting goals; for a literature review, see [3]. For example, Mosetti et al. apply a genetic algorithm (GA) to a discrete design space; Dupont and Cagan adopt a continuous design space [4,5]; Chowdhury et al. propose a new method called Unrestricted Wind Farm Layout Optimization for placing turbines in a farm [6]; and Messac et al. consider WFLO with uncertain wind resource [7]. Chen and MacDonald (the authors) add to this work a model of uncertain landowner participation rates [3], upon which this paper builds.

When the wind farm is being placed on an area of land owned by individual landowners, each landowner must decide whether or not they want to participate in the project and lease their land to a developer, typically in exchange for monetary compensation. The amount of money the landowner receives is called the remittance cost, see Section 2.1.1. Landowners' decisions and concerns have a great impact on the implementation of the wind farm project, and can lead to project failure [8–12]. One possible community response to a wind farm is NIMBY (Not In My Backyard), an emotionally complex response. As Wüstenhagenet al. [13] discuss, at first, landowners are excited about the project. As they learn more about the potential downsides of participating in the project, such as impacts on crops and potentially obstructed views, the support for the project decreases. As the project proceeds and the details are finalized, support increases again. This trend is reflected in the associated property values. Hoen et al. [14] find that during the development stages of the wind facility, the value of nearby property decreases. However, when all the construction is completed, the property value increases again. Fig. 1 illustratively shows the congruent trends identified in these two studies: a dip in acceptance in the time when developers most need acceptance to

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http://dx.doi.org/10.1016/j.enconman.2013.10.003

Nomenclature

$AEP_{tot}(X)$	total energy output of the farm
c	cell label, $c \in \{1, 144\}$
$C(X)$	levelized cost per year of a wind farm
C_{a1}	assembly and installation cost for a single turbine
C_{ac}	annual compensation per MW in 2002 dollars
$C_{aot}(X)$	total annual operating expenses for a wind farm
C_{b1}	balance station cost for a single turbine
C_{e1}	electrical interface/connections cost for a single turbine
C_{f1}	foundation cost for a single turbine
C_{ic1}	initial capital cost for a single turbine
C_{ict}	total levelizedinitial capital cost for a wind farm
$C_{llt}(X)$	total land lease cost per year for a wind farm
$C_{omt}(X)$	total levelized maintenance cost per year for a wind farm
C_{p1}	engineering and permits cost for a single turbine
C_{r1}	road and civil cost for a single turbine
$C_{rot}(X)$	total levelized replacement/overhaul cost per year for a wind farm
C_{t1}	transportation cost for a single turbine
C_{ts1}	turbine system cost for a single turbine
$COE(X)$	cost-of-energy
D	rotor diameter
$h_0(X)$	equality constraint
$h_c(X)$	equality constraint c
i	turbine index, $i \in \{1, N\}$
k	bits index, $k \in \{1, 153\}$
$L(X)$	total number of landowners who say yes
m	row number of cell c
$N(X)$	total number of turbines
n	column number of cell c
n_{yes}	preset number of landowners who say yes, n_{yes} = 4, 5, or 6
$p(u_0, \theta)$	probability of occurrence for ambient wind speed u_0 in direction θ
$P_i(u_i(u_0, \theta))$	power output of turbine i as a function of the effective wind speed of turbine i
P_r	machine rating of the turbine
q	magnitude of the penalty
r_1	effective downstream radius of the wake
r_{fc}	fixed charge rate
r_r	Rotor radius
t	landowner index, $t \in \{1, 9\}$
u_0	ambient wind speed for turbine i
u_{0max}	maximum ambient wind speed for turbine i
u_i	effective wind speed of turbine i in the wake of n upstream turbines
$u_i(u_0, \theta)$	effective wind speed of turbine i for an ambient wind speed u_0 and a wind direction θ
u_{ij}	effective downstream wind speed for turbine i affected by the wake of upstream turbine j
X	153 bits binary string design variable
x	X-coordinate of potential turbine in cell c
X_k	kth bit of binary string X
y	Y-coordinate of potential turbine in cell c
z	hub height of the turbine, z = 80 m
z_0	surface roughness of ground, z_0 = 0.055 m
α	entrainment constant
θ	wind direction
$\varphi(X, c)$	constraint that a turbine can only be placed in the land cell of an owner who says yes
$\phi(X)$	penalty function

proceed with project planning. Negotiations between wind developers and landowners can be difficult during this time. Wind developers are unsure of the final design of the farm, and understandably want to keep all options for development available. The contracts they offer landowners are for access to the entire plot of land, with no guarantee on the noise impact, visual impact, construction impact on crops, or inconvenience during turbine installation and maintenance (beyond what is regulated by applicable zoning laws). Landowners are offered a compensation package that is very difficult to value, as they are given incomplete information on how the turbines will impact their lifestyle and land. Due to the confidential nature of the wind industry, the negotiation process and compensation information are not often disclosed to public [15]. According to NREL's Wind Turbine Design Cost and Scaling Model (WTDC&S) [16], no model is available to predict land lease costs—this also indicates a need for more attention to landowner issues in technical academic research.

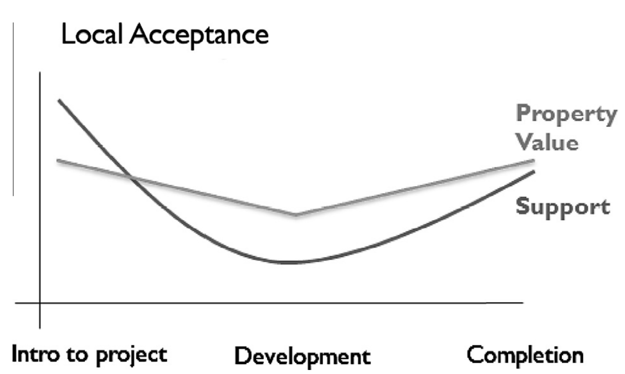

Fig. 1. Property value and support for wind farm projects have congruent trends.

The authors propose, based on interviews with landowners and representatives from small- and large-scale developers, that more information earlier in the development process would lead to smoother negotiations. For example, it would be helpful to developers, and also to landowners, to have an understanding of where turbines will be placed earlier in the wind farm development timeline. This could be done using wind farm layout optimization. Yet, one important assumption included in wind farm optimization layout research is that all of the land in a given region is readily available for use. In reality, a continuous piece of land is not readily available until negotiations with landowners have concluded—and potentially never available, depending on which landowners agree to participate in the project. The availability of land controls, in-part, the final layout of the turbines.

Developers also need an accurate prediction of a project's financial viability, or cost-of-energy (COE). Minimizing COE, which aims to generate the maximum amount of energy with minimum cost, is often represented in the objective function of a WFLO as a pseudo-COE formulation, considering only the cost of total number of turbines, as in [4,5,17–19], and ignoring other important costs. To address this limitation, we adopt a more realistic COE formulation, in which the cost of running the farm is estimated on a yearly basis and divided by the predicted annual energy output of the farm, to estimate the real cost in dollar per unit energy produced. The estimated COE can then be compared with the actual collected market COE data to evaluate the viability of the project.

The authors' previous work [3] relaxes the assumption that a continuous piece of land is available in a wind farm layout optimization.