Optimal Locations for Siting Wind Energy Projects: Technical Challenges, Economics, and Public Preferences

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Abstract

Increasing the percentage of wind power in the United States electricity generation mix would facilitate the transition towards a more sustainable, low-pollution, and environmentally-conscious electricity grid. However, this effort is not without cost. Wind power generation is time-variable and typically not synchronized with electricity demand (i.e., load). In addition, the highest-output wind resources are often located in remote locations, necessitating transmission investment between generation sites and load. Furthermore, negative public perceptions of wind projects could prevent widespread wind development, especially for projects close to densely-populated communities. The work presented in my dissertation seeks to understand where it’s best to locate wind energy projects while considering these various factors.

First, in Chapter 2, I examine whether energy storage technologies, such as grid-scale batteries, could help reduce the transmission upgrade costs incurred when siting wind projects in distant locations. For a case study of a hypothetical 200 MW wind project in North Dakota that delivers power to Illinois, I present an optimization model that estimates the optimal size of transmission and energy storage capacity that yields the lowest average cost of generation and transmission ($/MWh). I find that for this application of storage to be economical, energy storage costs would have to be $100/kWh or lower, which is well below current costs for available technologies. I conclude that there are likely better ways to use energy storage than for accessing distant wind projects.

Following from this work, in Chapter 3, I present an optimization model to estimate the economics of accessing high quality wind resources in remote areas to comply with renewable energy policy targets. I include temporal aspects of wind power (variability costs and correlation to market prices) as well as total wind power produced from different farms. I assess the goal of providing 40 TWh of new wind generation in the Midwestern transmission system (MISO) while minimizing system costs. Results show that building wind farms in North/South Dakota (windiest states) compared to Illinois (less windy, but

close to population centers) would only be economical if the incremental transmission costs to access them were below $360/kW of wind capacity (break-even value). Historically, the incremental transmission costs for wind development in North/South Dakota compared to in Illinois are about twice this value. However, the break-even incremental transmission cost for wind farms in Minnesota/Iowa (also windy states) is $250/kW, which is consistent with historical costs. I conclude that for the case in MISO, building wind projects in more distant locations (i.e., Minnesota/Iowa) is most economical.

My two final chapters use semi-structured interviews (Chapter 4) and conjoint-based surveys (Chapter 5) to understand public perceptions and preferences for different wind project siting characteristics such as the distance between the project and a person's home (i.e., "not-in-my-backyard" or NIMBY) and offshore vs. onshore locations. The semi-structured interviews, conducted with members of a community in Massachusetts, revealed that economic benefit to the community is the most important factor driving perceptions about projects, along with aesthetics, noise impacts, environmental benefits, hazard to wildlife, and safety concerns. In Chapter 5, I show the results from the conjoint survey. The study's sample included participants from a coastal community in Massachusetts and a U.S.-wide sample from Amazon's Mechanical Turk. Results show that participants in the U.S.-wide sample perceived a small reduction in utility, equivalent to $1 per month, for living within 1 mile of a project. Surprisingly, I find no evidence of this effect for participants in the coastal community. The most important characteristic to both samples was the economic benefits from the project – both to their community through increased tax revenue, and to individuals through reduced monthly energy bills. Further, participants in both samples preferred onshore to offshore projects, but that preference was much stronger in the coastal community. I also find that participants from the coastal community preferred expanding an existing wind projects rather than building an entirely new one, whereas those in the U.S.-wide sample were indifferent, and equally supportive of the two options. These differences are likely driven by the prior positive experience the coastal community has had with an existing onshore wind project as well as their strong cultural identity that favors ocean views. I conclude that preference for increased distance from a wind project

(NIMBY) is likely small or non-existent and that offshore wind projects within 5 miles from shore could cause large welfare losses to coastal communities.

Finally, in Chapter 6, I provide a discussion and policy recommendations from my work. Importantly, I recommend that future research should combine the various topics throughout my chapters (i.e., transmission requirements, hourly power production, variability impacts to the grid, and public preferences) into a comprehensive model that identifies optimal locations for wind projects across the United States.

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Chapter 1

1 Introduction

There is growing concern in the United States (U.S.) about how to reduce the emissions of criteria air pollutants and greenhouse gases (GHG) associated with fossil fuel electricity generation. Replacing current generation with renewable energy could provide part of the solution since most renewable technologies do not produce emissions and provide long-term sustainable sources of energy. In 2008, a report by the U.S. Department of Energy (DOE, 2008) suggested that wind energy could provide 20% of electricity generation in the U.S. by 2030. A follow up report in 2015 showed that the U.S. is on track to meet this target with 224,000 megawatts (MW), triple current wind capacity (DOE, 2015). The U.S. Federal government promotes this increase with incentives such as the PTC (production tax credit) which provides a corporate tax credit equal to $23 per MWh of electricity generated from renewable projects, like wind energy. It was initially enacted in 1992 (at a lower rate), but was extended 10 times, including recently until the new expiration in 2019. Between 2014 and 2018, the PTC will provide an estimated $16 billion in total financial incentives for renewable projects (Sherlock, 2015). In addition, 29 states and Washington, DC have implemented renewable portfolio standards (RPS), which require a minimum percentage of electricity demand to come from qualifying renewable resources (DSIRE, 2015). It is expected that wind will be the largest contributor to these targets.

Many studies have analyzed the challenges with integrating wind energy into the electricity grid in the United States. Jacobson and Delucchi (2011) claim that adding large amounts of renewable generation to the world's electricity mix can provide energy at costs equal to current costs. However, others such as Trainer (2012) strongly disagree, and argue that when the true cost of power variability is accounted for, renewable integration – especially at such a large scale – causes substantial increases in energy costs.

DeCarolis and Keith (2005) showed that increasing wind power to serve 50% of demand adds about $10-20/MWh to the cost of electricity due to the variability of wind power output and the increased capital cost incurred to build supporting transmission capacity. Lueken et al. (2012) analyzed the variability of 20 wind farms in Texas over one year and concluded that costs due to variability are on average $4/MWh, when using ancillary service costs in California as an estimate for variability cost.

In addition to power variability, there are also challenges with economically accessing wind power. Many of the highest quality onshore wind resources in the U.S. and abroad are located in areas that are far away from load centers and therefore lack sufficient transmission capacity to deliver power to the grid. The alternative to accessing these distant resources is to build farms closer to electricity consumers and thus take advantage of existing transmission capacity. However, these closer sites may have lower wind speeds, resulting in lower electricity output per farm. Furthermore, locating farms close to households may be met with opposition, leading to suboptimal solutions and potentially failed project development. Therefore, the question of whether to build wind farms in remote locations (far from homes) or local locations (close to homes) deserves attention.

Trade-offs between wind resources and transmission investments are particularly interesting in the case of the U.S. Midwestern electricity grid, MISO (Midcontinent Independent System Operator), which spans 15 states. Most existing infrastructure in MISO is located East, in states like Illinois. For example, in 2012, 21% of total electricity sales were within Illinois, the most populous state in MISO. Including sales in the neighboring states of Missouri and Indiana, this percentage increases to 49%. In contrast, states that are more remote from major load centers such as North and South Dakota collectively account for only 4% of MISO's electricity sales[1](EIA, 2014). Compared to wind farms in North Dakota, Illinois wind farms tend to have lower transmission interconnection costs, as there is already a robust network of

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[1] For simplicity, we used total electricity sales within each state that is in MISO, even though some states are only partially in MISO. We did not include states within MISO's Southern region since they are outside the scope of our study's geographical focus.

existing infrastructure (high voltage lines, substations, etc.). However, wind speeds tend to be higher in the Dakotas. For example, according to power output data of hypothetical wind farms from the National Renewable Energy Laboratory (NREL), North and South Dakota wind farms result in average capacity factors of 43% compared to 40% in Illinois (EWITS, 2012). At first glance this difference may appear small, but it accounts for a cost difference of $1.4 billion in upfront costs when trying to meet a wind generation target of 40 terawatt-hours (TWh) per year (equivalent to renewable targets in MISO), assuming that installed capital cost for wind farms are $1,750/kW. Therefore, it's not obvious where it's most economical to build new wind farms to meet MISO's renewable targets.

Another important consideration when integrating wind power is public perception. According "National Wind Watch," an advocacy group, there are 219 organizations (134 with websites) across the U.S. that oppose or take action against wind projects in their area (2014a). The most common reasons for opposition include visual impacts to the landscape, concerns about noise from the turbines, perceived economic costs as well as inefficiencies, and hazard to wildlife (Devine-Wright, 2005a; Wolsink, 2000). Past literature shows a disconnect between approval of wind farm development by the general public, and disapproval by local communities directly affected by projects (Devine-Wright, 2005b; Van der Horst, 2007; Wolsink, 2000). This phenomenon is often referred to as the NIMBY (not-in-my-backyard) effect – a preference for not having wind projects near one's home, even though the person may support wind development in general. One could argue that communities would reject any power plant near them, regardless of technology. However, wind projects require more land per MW than conventional generators and are easily visible since they are often are over 400 feet tall. Therefore, building wind projects in more distance locations with fewer households may offer additional advantages over local locations when considering public preferences.

Public perception concerns are particularly salient in Massachusetts, which is poised to become a leader in wind energy given its ambitious goal of building 2,000 MW of wind power by 2020 compared to today's installed capacity of 100 MW (2015; U.S. Geological Survey, 2015). The region's geography is unique since it offers the possibility of onshore and offshore projects, both of which are being pursued aggressively. State legislatures recently passed a bill that requires utilities to procure 1,600 MW of offshore wind by 2027 (Harvey, 2016). However, despite large general public support for it, offshore development has also provoked considerable controversy in Massachusetts. The infamous 130 turbine Cape Wind project in Nantucket Sound off Cape Cod recently failed to gain approval (McNamara, 2015). Even in 2007, during the project's early-stages, only 58% of nearby residents were supportive compared to 84% among all Massachusetts residents (Civil Society Institute, 2007). It remains to be seen how residents across the State will react to new wind project proposals.

My research addresses several issues related to the consequences of where to build wind projects, and is most relevant to policymakers and project developers faced with siting decisions. In my Chapter 2, I examine whether energy storage capacity, such as gird-scale batteries, would help reduce the transmission upgrade costs incurred when developing remote wind farms in MISO. Chapter 3 describes an optimization model that finds the lowest-cost locations for wind projects to meet an annual wind generation target in MISO. The model considers wind power output, localized transmission costs, and the potential negative impacts to the electricity grid resulting from increased hourly power variability brought on through additional wind capacity. Building from these results, Chapters 4 and 5 describe a public perceptions study that estimates the monetary value households place on different aspects of wind projects, including proximity to them (i.e, NIMBY) as well as their preference for onshore versus offshore projects. Chapter 4 presents results from 15 in-person interviews of residents in a coastal community in Massachusetts. The interview findings helped develop a conjoint-based choice survey, which I use to estimate willingness-to-accept (WTA) values (in $/ month) of different project attributes. Chapter 5 presents survey results based on a sample from the same Massachusetts community as well as from a broader sample across the U.S. The final chapter concludes with broader implications of this work.

Chapter 2

2 The role of energy storage in accessing remote wind resources in the Midwest

This work has already been published in *Energy Policy* as the reference below. The chapter uses "we" instead of "I" to reflect the contributions of my co-authors.

> *Lamy, Julian, Inês L. Azevedo, and Paulina Jaramillo. "The Role of Energy Storage in Accessing Remote Wind Resources in the Midwest." Energy Policy 68 (May 2014): 123–31. doi:10.1016/j.enpol.2014.01.008.*(Lamy et al., 2014)

2.1 Introduction

There is growing concern in the United States about how to reduce the emissions of criteria air pollutants and greenhouse gases (GHG) associated with fossil fuel electricity generation. Replacing current generation with renewable energy could provide part of the solution since most renewable technologies do not produce emissions and provide long-term sustainable sources of energy. In 2008, a report by the U.S. Department of Energy (DOE, 2008) suggested that wind energy could provide 20% of electricity generation in the U.S. by 2030. Federal and local governments in the United States are promoting an increase in renewable capacity with incentives such as the federal production tax credit for wind power. In addition, 29 states and Washington, DC have implemented renewable portfolio standards (RPS) calling for up to 40% of generation coming from qualifying renewable resources (DSIRE, 2015). It is expected that wind will be the largest contributor to these targets. However, in order to meet these ambitious targets, many questions about integrating wind resources must be answered.

Many studies have analyzed the challenges with integrating wind into the electricity grid in the United States, and most of that work has focused on the variability of wind power. For example Jacobson and Delucchi (2011) claim that adding large amounts of renewable generation to the world's electricity mix can provide energy at costs equal to current costs. Others such as Trainer (2012) argue that when the true cost of power variability is accounted for, renewable integration, especially at such a large scale, does indeed incur nontrivial increases in energy costs. DeCarolis and Keith (2006) showed that increasing wind power to serve 50% of demand adds about $10-20/MWh to the cost of electricity due to the intermittency of wind power output and the increased capital cost incurred to build supporting transmission capacity. Lueken et al. (2012) analyzed the variability of 20 wind farms in ERCOT over one year and concluded that costs due to variability are on average $4/MWh, when using ancillary service costs in California as an estimate for variability cost.

There has also been considerable attention recently to the application of energy storage to integrate wind power and handle variability concerns. Greenblatt et al. (2007) and Hittinger et al. (2010) explored how wind could be used as baseload power when coupled with energy storage capacity and natural gas generation. Denholm et al. (2005) performed a similar analysis that concluded that wind could have as high as 80% capacity factor (similar to coal and nuclear generators) when coupled with compressed air energy storage (CAES).

Other papers have focused on the profitability of using energy storage in current energy markets. Fertig and Apt (2011) analyzed the economics of a hypothetical integrated CAES-wind farm system in Texas that takes advantage of price arbitrage opportunities. They found that in most scenarios, the unit was unprofitable when participating in real-time energy markets in ERCOT. Similarly, using a stochastic dynamic programming model that accounts for uncertainty in hourly prices and wind power, Mauch et al. (2012) found that a wind-CAES system participating in day-ahead markets would not be profitable, even with a carbon price of $20 to $50 per tonne CO_2.

In addition to power variability, there are also challenges with economically accessing wind power. Many of the highest capacity factor wind resources are located in areas that are far away from load centers and therefore require large transmission investments. The alternative to accessing these distant resources is to build local wind farms that often have lower wind potential but require lower transmission investments. Hoppock and Patiño-Echeverri (2010) studied the problem of whether it is more economical to integrate wind (up to 10 TWh of wind generation) in local or remote locations to comply with the Illinois RPS and concluded that local resources in Illinois provide the least costly investment. They used the average annual capacity factor of different sites at varying distances in the Midwest to estimate the average cost of each site ($/MWh), including the costs of transmission needed to access distant farms. They found that the major cost-driver that prevents remote wind development is transmission costs, which ranged from $1,200 to $4,200/MW-km in their analysis.

In addition to the transmission costs assumed by Hoppock and Patiño-Echeverri (2010), there is a wide range of cost estimates used throughout the literature. In their economic analysis of CAES in Texas, Fertig and Apt (2011) developed a transmission cost model using historical data. This model was developed using actual transmission costs that ranged from $200 to $900/MW-km. Similarly, Denholm and Sioshansi (2009) reported transmission costs ranging from $100 to 1,300/MW-km. Further, as highlighted in Fischlein et al. (2013), transmission investments will require considerable coordination among local and federal government. Issues such as siting, line planning, and permitting are non-monetary costs that add complexity to building transmission projects. Careful treatment of the uncertainty in transmission costs is therefore important when modeling the economics of remote wind projects.

One solution to reducing transmission costs associated with accessing remote wind is to reduce the capacity of the transmission line available to the remote farm. Because wind farms rarely generate at full capacity --average capacity factors range between 25% and 50% for farms within the Eastern Interconnect (EWITS, 2012) -- the optimal transmission capacity to access one farm is less than the farm's full capacity. Pattanariyankool and Lave (2010) showed that the optimal transmission capacity needed to access a remote farm ranges from 70 to 80% of the farm's nameplate capacity. They assumed that the farm incurs capital cost of transmission per unit of capacity (MW) and therefore with less capacity, the project would save on costs. The caveat, however, is that during times that the farm generates more electricity than this transmission capacity, the operator would have to curtail power and forego revenue from energy sales. Finding the optimal level of transmission is therefore nontrivial.

Investors and operators could further reduce the costs of accessing remote wind power if the wind farm had the ability to store electricity during times that transmission is constrained, and sell it later when transmission is not constrained. This would allow the operator to avoid wind curtailment as well as perhaps reduce required transmission capacity even further. Using 2005 day-ahead prices in PJM, and hourly wind output data from EWITS (2008), Denholm and Sioshansi (2009) compared the revenue when siting CAES at a remote wind farm as opposed to siting it at load and operating it independently from the remote wind farm. At both locations, the operator is assumed to use the storage device for price arbitrage in day-ahead energy markets. When the storage capacity was co-located with the wind farm, the optimal transmission capacity would decrease since the operator could better control power delivered on the line and therefore reduce transmission capacity investment. However, this arrangement limits the operator's ability to arbitrage prices since transmission constraints may limit the availability of the storage device compared to when it is located at load. It is this tradeoff in revenue that they used to estimate the break-even cost of transmission at which point building energy storage on-site becomes economical.

Denholm and Sioshansi (2009) results showed that for transmission costs above $450/MW-km in the Upper Midwest, energy storage (up to 30% of a wind farm's capacity) starts to replace transmission capacity for optimal profits. While the authors used a wide range of transmission costs in their analysis, they did not vary storage costs, which are highly uncertain. It is also uncertain whether market participation would be the most economic financing arrangement for such a project, as opposed to fixed-price power purchase agreements.

In this chapter we study the application of energy storage to reduce transmission capacity required to access remote wind resources. As a case-study, we focus on a wind farm in North Dakota that is built to deliver power to Illinois, and estimate the break-even capital cost of energy storage at which point it becomes an economic alternative to transmission capacity. We selected these locations because wind capacity factors are high in much of North Dakota but these farms are far away from major load centers, mainly located in Illinois.

Since transmission costs affect the viability of remote wind farms, we also find the break-even cost of transmission. To do this, we parameterize the size and costs of energy storage and transmission capacity to access the farm, and find the transmission and storage sizes that yield the lowest average cost of generating and delivering electricity ($/MWh) to end-users. This is equivalent to the annualized cost of a power plant when including transmission (Kammen and Pacca, 2004). An optimization model is developed to estimate the hourly operation of the energy storage asset given its size and the available transmission capacity. A benefit of our approach is that it provides a realistic metric for evaluating projects that could be used to set a minimum negotiated price target for a power purchase agreement. The approach also avoids making assumptions about hourly energy prices, which are highly volatile and uncertain, especially as installed wind capacity increases.

The rest of the chapter is organized as follows: the next section describes the proposed project and frames the problem. Section 2.3 describes the modeling method, Section 2.4 presents results, and Section 2.5 discusses the implications of our results.

2.2 Wind-Storage Transmission System

2.2.1 Location and characteristics

We focus on the Midwest, and Illinois in particular, because of the ambitious renewable targets in this state and the general characteristics of wind power in the Midwest. Illinois has an RPS requiring 25%

renewable generation by 2025, and 60-75% of this target must be met by wind power (either in or out of state). Meeting this goal would require building approximately 10 Gigawatts (GW) of new wind capacity by 2025, which would double the installed wind capacity in the entire Midwest region[1]. Illinois has good wind resources but it is also surrounded by other states that have the best onshore wind potential in the United States[2]. It is therefore an interesting area in which to study how to access remote resources since doing so might prove to be an attractive investment.

In choosing the wind site for our analysis, we relied upon wind power output data simulated by the National Renewable Energy Lab (NREL) for the Eastern Wind Integration and Transmission Study (EWITS). For this study, NREL estimated wind energy potential for over 1,300 sites across the United States. NREL first published the data in 2008 but has since updated their estimates in the summer of 2012 (EWITS, 2012). At each site, NREL estimated the maximum capacity of the wind farm and simulated the resulting wind power output from 2004 to 2006 in 10-minute increments. We chose to analyze the integration of the best wind farm in the Midwest according to EWITS, which is 200 MW, has an average capacity factor of 46% from 2004 to 2006, and is located in North Dakota, 1,200 km from the Illinois Hub price node. Figure 2.1 displays the energy system under study.

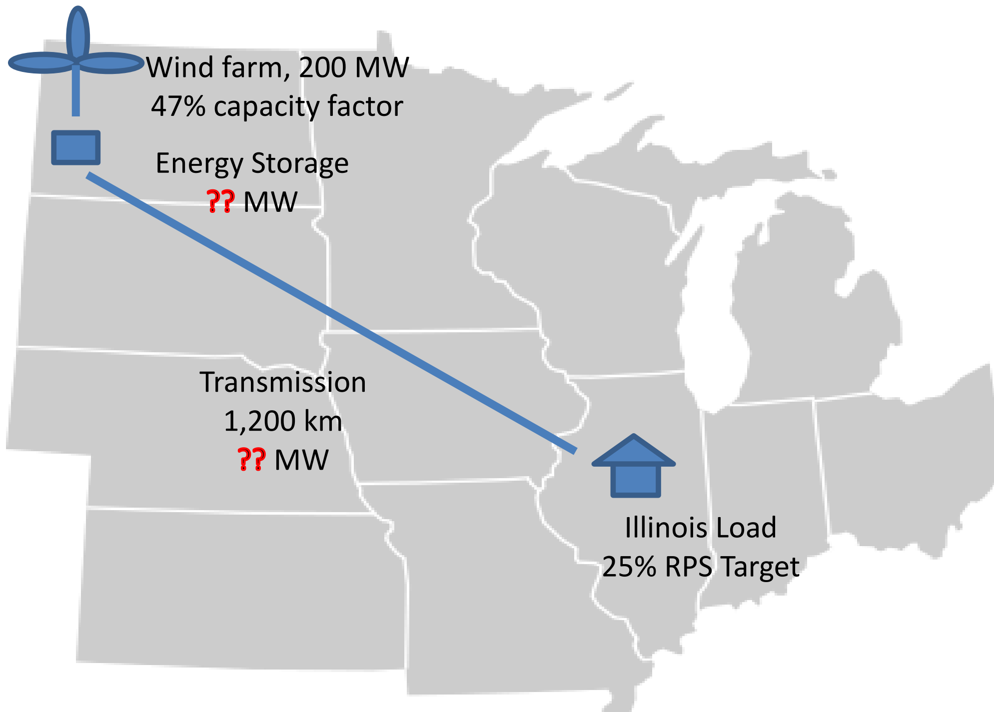


Figure 2.1: Map of the Midwest region and the proposed remote wind farm in North Dakota, built to serve load in Illinois. The objective is to find the sizes (MW) of transmission and energy storage that minimize the costs of generating and delivering power.

2.2.2 Investment Decision

We study the case where a single agent builds a 200 MW wind farm in North Dakota to deliver power to Illinois. We assume that this agent must also build the infrastructure necessary to deliver the power to load (i.e., transmission and storage). Thus, the agent has to decide how much transmission and energy storage capacity to build to access the farm. We suggest that the objective of the agent is to minimize the project's average cost of generating and delivering electricity (ACE). Unlike other studies that report ACE as the cost of only generating electricity, the ACE estimates shown in the results Section 2.4 include *both* the costs of producing *and* delivering wind power to load. ACE is calculated by dividing the sum of annualized capital costs and variable costs for all assets by the total power delivered in one year, as shown in Equation (1). The ACE, however, is not the objective of the optimization model that we develop. Instead, a set of scenarios with different transmission and storage size combinations are defined and evaluated using an optimization model that maximizes total delivered power for each scenario. Results from these scenarios are then used to evaluate the combinations of sizes that yield the lowest ACE under various capital cost assumptions. This will be further detailed in Section 2.3 of this chapter.

$$\text{ACE} = \frac{\underset{\text{(Transmission, Storage, Wind)}}{\text{Annualized capital cost}} + \underset{\text{(Storage, Wind)}}{\text{Variable cost for 1 year}}}{\text{Total MWh delivered per year}} \quad (1)$$

It could be argued that the investment decision should be based on the profitability of the project, and in fact previous studies (Denholm and Sioshansi, 2009; Fertig and Apt, 2011; Mauch et al., 2012) used profit maximization in the economic analysis of storage-wind systems. We argue, however, that given the unique characteristics of the electricity markets, predicting profits using market prices is highly uncertain. We further suggest that the average cost of generating and delivering electricity (ACE) is a measure of the minimum average price the developer would need to recover costs, and could be used as a benchmark to negotiate a power purchase agreement with an electric utility. Alternatively, if the investor of this project instead participates in energy markets directly, then ACE provides a lower bound for the average market price (minus any government incentives) that the project would need to receive in order to recover costs.

2.2.3 Cost Tradeoff between Transmission and Energy Storage

If an energy storage technology is cost competitive, then adding storage might incentivize the decision-maker to reduce the necessary transmission investment to access remote wind power. This tradeoff, however, relies on the assumption that transmission capacity can be scaled down linearly by capacity and distance ($/MW-km). While we make this assumption, which Denholm and Sioshansi (2009); Fertig and Apt (2011); and Pattanariyankool and Lave (2010) also made, it still deserves some attention. Some costs -- such as property rights, siting, and right of way -- are not scalable. It's likely that these costs will be unaffected by the size of the line built since they must be incurred for any project size.

A report by American Electric Power (AEP, 2006) summarized the transmission costs for a proposed line from West Virginia to New Jersey. AEP broke out the estimates of transmission costs by cost item, as summarized in Table 2.1. If we assume that all equipment and construction costs for the substations and lines are scalable by MW, then about 80% of the costs are scalable. We thus assume that this assumption holds true for transmission lines and that calculating transmission costs with a scalable $/MW-km metric is a reasonable approach.

Scalability is also consistent with the more recent development of subscribed transmission lines. As opposed to traditional transmission projects, subscribed lines require generators to enter private contracts with the line owner to use the line. For example, for the Rocky Island Clean Line generators must negotiate contracts to use specified amounts of capacity (Clean Line Energy Partners, 2015). If optimal to do so, generators could scale down their allocated transmission capacity from the contract and replace it with energy storage. We thus assume that the maximum amount of transmission that one single farm would purchase is 100% of the nameplate capacity of the farm, 200 MW in this case, and that the costs are linearly scalable by capacity and distance.

Table 2.1: Cost items for the AEP interstate transmission project from West Virginia to New Jersey ($ 2006). (Source: AEP (2006))

Item	**Category**	**$ Million**
Amo Substation		30
Doubs Substation	Equipment	154
	Property	2.5
Deans Substation	Equipment	169
	Property	2.5
765 kv line	Siting	94
	Right of way	516
	Line equipment & construction	1,968
Total Costs		2,936
Scalable Costs		2,321
% Scalable		79%

2.2.4 Operational Decision

We assume that a single agent builds and operates the wind farm and the infrastructure necessary to deliver power to load. We use average cost of generating and delivering electricity as defined in Equation 1 above (in $/MWh) as a metric to evaluate the size of storage and transmission to be built. We do this analysis via scenario comparison, as detailed in Section 2.3. If energy storage capacity is built, we assume that it will be used to maximize the total power delivered. There are considerable costs due to the variability of wind power as well as different values of electricity depending on the hour of the day (DeCarolis and Keith, 2006; Lueken et al., 2012). However this work does not consider these factors. Wind power is assumed to be a “must-take” resource, no matter when it is generated or what electricity market prices are at the time. We therefore assume that the agent is only interested in maximizing the total power delivered from the farm given that capital assets are already in place.

2.3 Method and Assumptions

2.3.1 Method Overview

In order to estimate the sizes of transmission and storage that yield the lowest average cost of generating and delivering electricity, we rely on scenario analysis. We first parameterize transmission and storage sizes over wide ranges. We vary transmission size from 60% to 100% of the nameplate capacity of the farm (200 MW), in 1% increments. We vary energy storage capacity from 0% to 100% of the nameplate capacity of the farm, in 10% increments. We also vary storage at a smaller scale, 0-10% in 1% increments to see if small amounts of storage prove to be economical. Under each set of assumptions, we then use an optimization model to maximize the total delivered power from the wind-storage-transmission unit. We rely upon 2006 wind data from EWITS (2012) for the power output of the North Dakota site. We then calculate ACE ($/MWh) over one year given assumed capital costs for transmission and storage. Figure 2.2 summarizes our modeling approach.

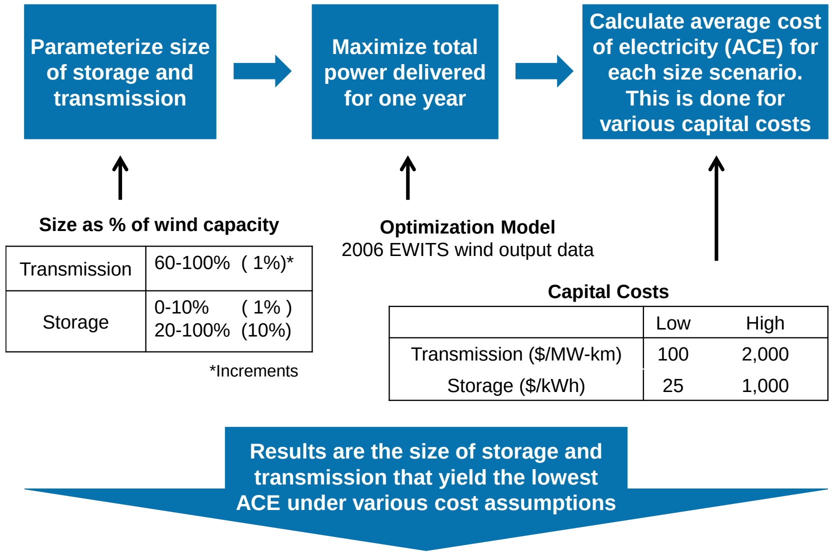


Figure 2.2: Modeling approach used to find the size of transmission and storage that yield the lowest average cost of electricity (ACE, $/MWh) for the proposed project.

2.3.2 Assumptions

Due to the large uncertainty in capital costs for transmission and storage assets, we range transmission costs from $100 to $2,000/MW-km and storage costs from $25 to $1,000/kWh. These ranges are consistent with values reported for different storage technologies, as shown in Table 2.2. Note that while we use ranges of costs from the literature, we are not making any statements about the plausibility of transmission or storage reaching the low costs in our tested ranges. We also do not assess the technical feasibility of the different technologies in the region studied. We treat costs parametrically and calculate the break-even costs at which point the optimal decisions change.

Table 2.2: Cost estimates of energy storage technologies and transmission.

Energy Storage Technologies	**$/kWh**	**Year $[i]**	**Source**	**Notes**
CAES (underground)	60-125	2010$	[(EPRI, 2010), Table 4-12]	-
Sodium-sulfur	~500	2010$	[(EPRI, 2010),, Table 4-14]	-
Li-ion	300-1,700	2010$	[(ANL, 2011); (EPRI, 2010), Table 4-14]	Low estimate is for 2020
Used Li-ion[ii]	40-130	2012$	(Neubauer et al., 2012)	Estimate is for 2020
Transmission	**$/MW-km**			
	$200 - 900	2001$	(Fertig and Apt, 2011)	-
	$100 - 1,300	Parameterized	(Denholm and Sioshansi, 2009)	-
	$1,200 -4,200	2009$	(Hoppock and Patiño-Echeverri, 2010)	-

i: The year in which the cost is observed is the same year as the citation unless otherwise noted.
ii: Batteries once used in electric vehicles but then repurposed for electricity grid applications.

Table 2.3 shows additional assumptions made as well as citations upon which the assumptions were based. These include a 10% discount rate to annualize capital cost as well as different lifetimes of each capital asset. We assume roundtrip efficiency for energy storage of 80% and transmission losses of 7%. We assume that the capital cost of the wind farm is $2,200/kW. Annual fixed operating and maintenance costs (FOM) are assumed to be $30/kW for wind, $0 for transmission, and $2.5/kW for storage. Variable costs for wind and transmission are assumed to be $0, and $7/MWh for storage. Duration of the storage device is assumed to be 1 hour. Sensitivities to these assumptions are presented in Section 2.4.3.

Table 2.3: Cost and technology performance assumptions.

	Wind	Storage	Transmission
Lifetime (years)	20	10	40
Inv. cost ($/kw)	2,200[i]	(see Table 2.2)	(see Table 2.2)
length (km)	-	-	1,200
FOM ($/kw)	30[i]	2.5[ii]	0
Duration (hrs) [iii]	-	1[iv]	-
VOM ($/MWh)	0 [i]	7 [ii]	0
Efficiency		80% [ii]	93%[v]

FOM = fixed operation and management costs; VOM = variable operation and management costs.
i: Based on AEO (2012) technology cost assumptions
ii: FOM is based on costs for balance of power and power electronics for Li-ion batteries. VOM and efficiency are also based on Li-ion batteries. (Kintner-Meyer et al., 2011)
iii: Duration is the time that a storage unit can deliver its rated capacity. For example, a 100 kw battery with 1 hour duration can deliver up to100 kW for 1 hour, or 100 kWh total. A 100 kW battery with 2 hr duration could deliver 100 kW for 2 hours, but not 200 kW in one hour.
iv: Based on Li-ion battery but also generalizable for CAES. CAES traditionally has longer duration (15-20 hours) but by assuming 1 hour duration, CAES will simply not have a restriction on how much it can store in any given hour. Instead, it is assumed that its limit on hourly capacity is equal to the full cavern capacity, which represents a best case scenario for this technology.
v: Based on transmission losses of 7%, this corresponds to the average distribution and transmission losses in the U.S. according to the Energy Information Administration: (EIA, 2012)

2.3.3 Optimization Model

For each transmission and storage size, we use a linear programming optimization model that maximizes total power delivered from the project (the denominator in Equation 1). As shown in Equation (2), for each hour over one year the model chooses when to store, transmit, or curtail power given wind output, a storage constraint, and a transmission constraint.

$$\max_{s_{t+1},\, z_t,\ \text{for every } t = \text{hour}} \sum q_t$$

$$\text{(2)} \qquad \text{S.t.: } q_t = w_t + s_t - s_{t+1} - z_t, \quad 0 \le s_t \le SC, \quad 0 \le q_t \le TC$$

Where:
q_t = transmitted power
w_t = wind power produced
s_t = power available in storage
z_t = curtailed power
TC = transmission size
SC = storage size
t = time (hours)

The state variables in the optimization are the power available in the storage device in hour t (s_t), which is dynamically linked to the decision variable (s_{t+1}), and the wind power produced (w_t), for which we rely upon 2006 wind power output data from (EWITS, 2012). The model solves over a three-day receding horizon for each hour over one year. Hourly wind power is assumed to be known without error over the three-day horizon. Other studies that relied on wind forecasts to optimize storage, such as (Mauch et al., 2012), used a shorter time horizon, 48 hours, and account for the uncertainty in hourly wind power. We deliberately choose optimistic assumptions about wind power in order to design a best-case scenario for storage.

The decision variables are the power stored for the next hour (s_{t+1}) and the power curtailed (z_t). Ideally, the operator would not curtail any power; however, if in an hour the operator is constrained both with respect to transmission and storage, then curtailment is necessary. Using the model from Equation (2), we calculate the total annual power delivered by the wind farm.

2.4 Results

2.4.1 Sizing of Transmission and Storage

Figure 2.3a-b shows the transmission and storage sizes that yield the lowest average cost of electricity (ACE) to access the 200 MW farm in North Dakota for Illinois load, while maximizing power transmitted. As transmission becomes more costly, storage capacity is used to replace transmission. However, this only occurs when storage costs are less than or equal to $100/kWh. As expected, higher storage costs become more viable (lowest ACE) as transmission costs increase. For example, at $25/kWh, storage starts to replace transmission when costs are greater or equal to $600/MW-km. At $50/kWh, storage starts to replace transmission for costs that are greater or equal to $900/MW-km. At $75/kWh, storage starts to replace transmission for costs that are greater or equal to $1,200/MW-km. For costs of $100/kWh, storage replaces transmission for costs that are greater or equal to $1,700/MW-km. Lastly, beyond $100/kW storage is uneconomical.

Figure 2.3a shows that, regardless of the storage capacity available, transmission size never drops below 72% of the installed wind capacity. This demonstrates that there is a lower bound to the amount of transmission that must be built in order to deliver adequate amounts of power to make the project economical. Optimal transmission also never reaches levels higher than 95%, since the wind farm's capacity factor is below this limit in all hours. These results are consistent with Pattanariyankool and Lave (2010), who showed that without storage, optimal transmission size is between 70 and 80% of the nameplate capacity of the wind farm.

In some extreme cases (Figure 2.3b), optimal energy storage capacity can be up to 200 MW, the same size as the wind farm. For example, in cases when energy storage cost is $25/kWh and transmission costs are greater than $1,000/MW-km, optimal storage ranges from 20-100% of wind farm capacity. These scenarios however, correspond to only optimistic cases for storage and pessimistic cases for transmission. Furthermore, the average cost of electricity for these cases (Figure 2.3c) range from $99 to $126/MWh, which is high relative to other technologies, including wind farms that are closer to load (Lazard, 2011). At such high costs, it is unlikely that the remote wind project would be built.

We estimate that developing a wind farm at the North Dakota site, including transmission and potential storage investments, would cost between $72 and $127 per MWh. In cases where some level of storage investment is optimal, costs are at least $88 per MWh. These estimates give a rough approximation of the average price of electricity that the project would have to receive in order to recover all costs. Figure 2.3d shows average transmission capacity factor, given different sizes of storage and transmission that yield the lowest ACE. When less transmission is added, there is a higher capacity factor on the line and with the addition of storage capacity, the capacity factor increases further as it avoids some power curtailment. The transmission capacity factors range from 49% to 62% depending on the cost scenario. Total power delivered changes less than 6% among all cases, ranging from 823 to 778 GWh (Figure 2.3f). In addition to having a higher average capacity factor, the variability in power delivered also decreases with the addition of storage and the reduction of transmission capacity. Figure 2.3e shows that the coefficient of variation in hourly power output ranges from 0.57 to 0.64. Figure 2.4 illustrates the optimal operation of the wind-storage system when transmission capacity and storage capacity are 80% and 20% of the wind farm capacity, respectively. When wind output is higher than transmission capacity, storage is charged to avoid power curtailment and later discharged when transmission is not constrained. This results in smoother delivered power. Although we do not estimate the value of decreased variability, projects with less variability may be more valuable to system operators since they would likely require less ramping by other generators.

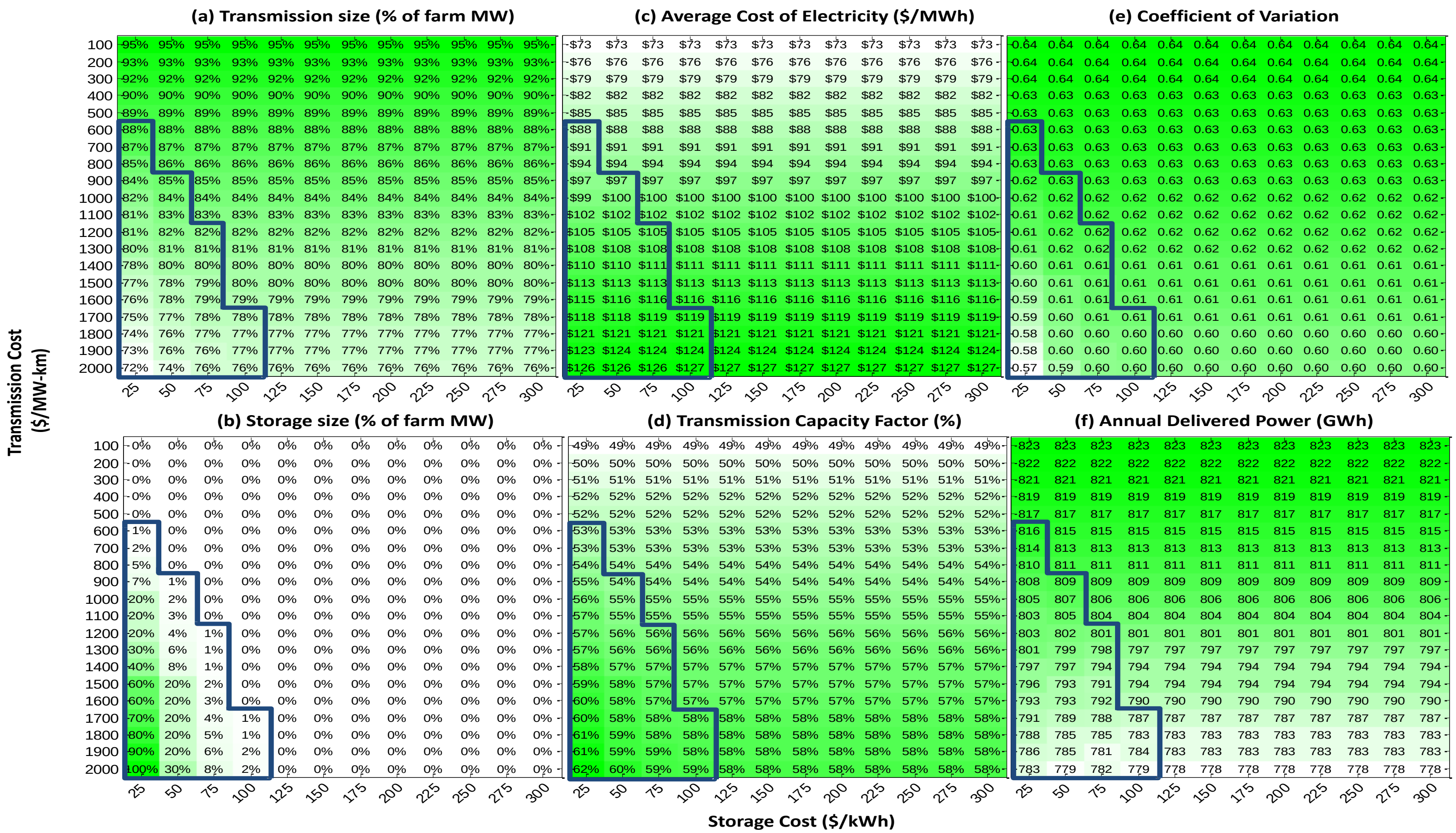


Figure 2.3 a-f: Figures show the results from finding the size of transmission and storage that provide the lowest average cost of electricity (ACE) for the North Dakota wind farm. For all figures, the y-axis represents the transmission costs (in $/MW-km) and the x-axis represents the storage costs (in $/kWh). Figure 2.3a shows the optimal size of transmission (as % of the wind farm's capacity, 200 MW), Figure 2.3b shows the optimal size of storage, Figure 2.3c shows the lowest ACE ($/MWh) achieved, and Figure 2.3d shows average transmission capacity factor (%).Figure 2.3e shows the coefficient of variation in hourly power delivered. Figure 2.3f shows total annual power delivered. The blue rectangles highlight the cases where storage capacity is ≥1% of total installed wind capacity. The shading shows how values in each figure compare (green represents highest values, white represents lowest values).

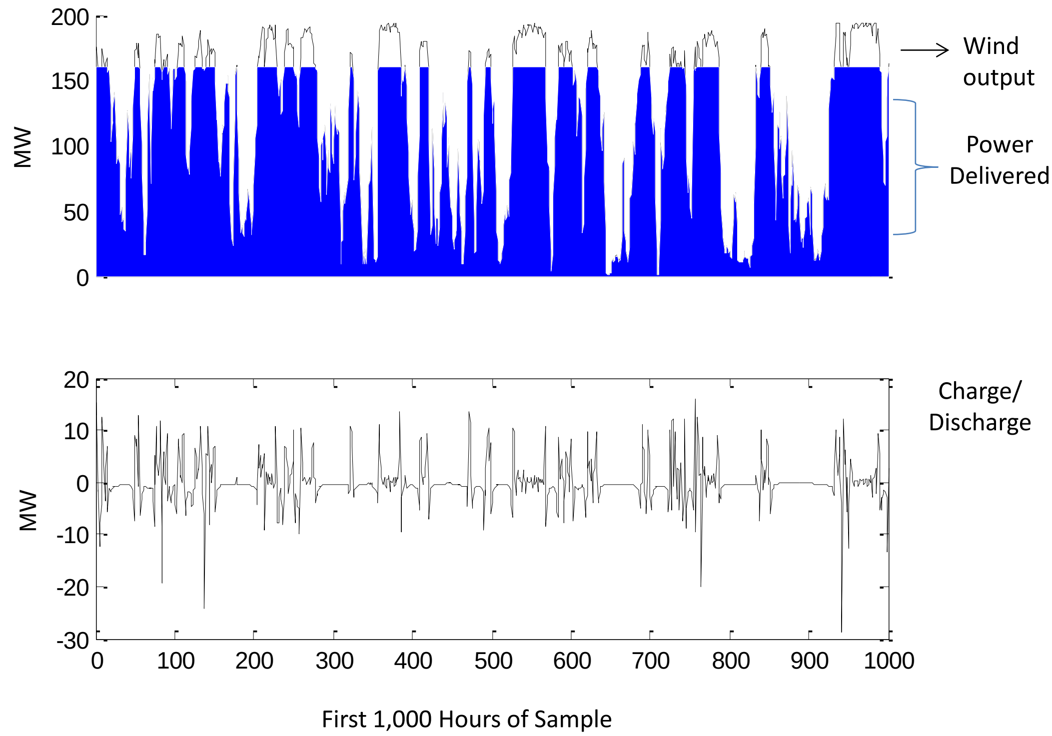


Figure 2.4: The figure displays results from maximizing total power delivered from the wind-storage system with 20% storage (40 MW) and 80% transmission (160 MW). The top figure shows the wind output relative to total power delivered from the wind-storage system. When wind output is greater than transmission capacity, storage (lower figure) is charged (positive values) to avoid curtailment. Storage is then discharged (negative values) in hours when more transmission capacity is available, thereby increasing the delivered power. The result is a smoothing effect on delivered power.

2.4.2 Trade-offs between transmission and storage

Storage does not easily replace transmission capacity economically because the marginal gains in power delivered from one more unit of storage is far lower than that gained by one unit of transmission. This issue is illustrated in Figure 2.5, which shows the marginal gain in power delivered with incremental size of storage (x-axis) and transmission (represented by curves). For example, when transmission size is 70% of wind capacity, increasing storage size from 0% to 100% of the farm's capacity adds about 25 GWhs of power delivered per year. Alternatively, the decision-maker could increase power delivered by the same amount by increasing transmission capacity by 5%. For the 200 MW farm considered, this corresponds to adding 200 MW of storage or only 10 MW of transmission. Despite this disadvantage however, as shown in Figure 2.3a, when storage is very inexpensive and transmission is expensive, optimal storage size can be up to 200 MW, the same size as the wind farm.

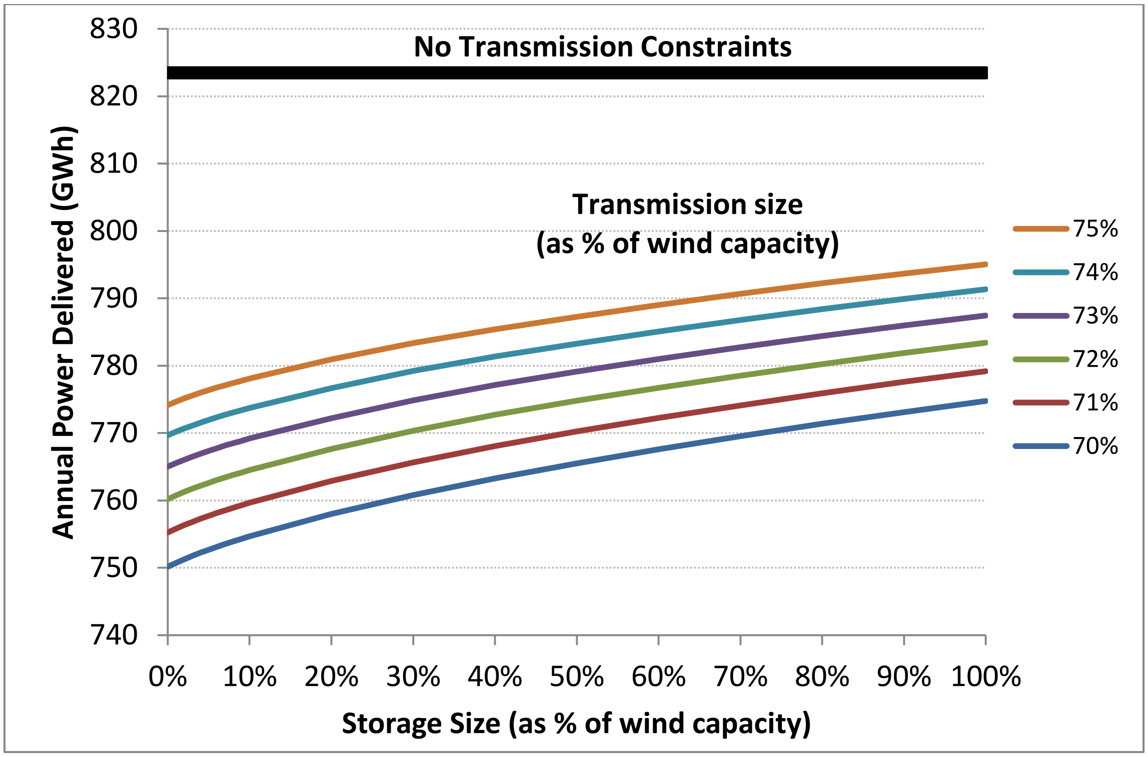


Figure 2.5: Annual power delivered as the size of storage (x-axis) and transmission capacity (curves plotted). Not all transmission sizes are plotted. The figure highlights how one unit of transmission capacity provides much more delivered power than one unit of energy storage capacity.

2.4.3 Sensitivity to key assumptions

Table 2.3 in Section 2.3.2 summarizes our assumptions of technology cost and performance characteristics for wind, energy storage, and transmission. To test the robustness of our results to these assumptions, we performed a sensitivity analysis by creating low and high cases for the most relevant assumptions (Table 2.4). The major factors affecting the economics of storage -- other than the capital costs of storage and transmission -- are storage lifetime, transmission lifetime, storage variable and fixed operating and maintenance costs (VOM and FOM), discount rate, and wind capital costs.

Table 2.4: Range of assumptions used in sensitivity analysis.

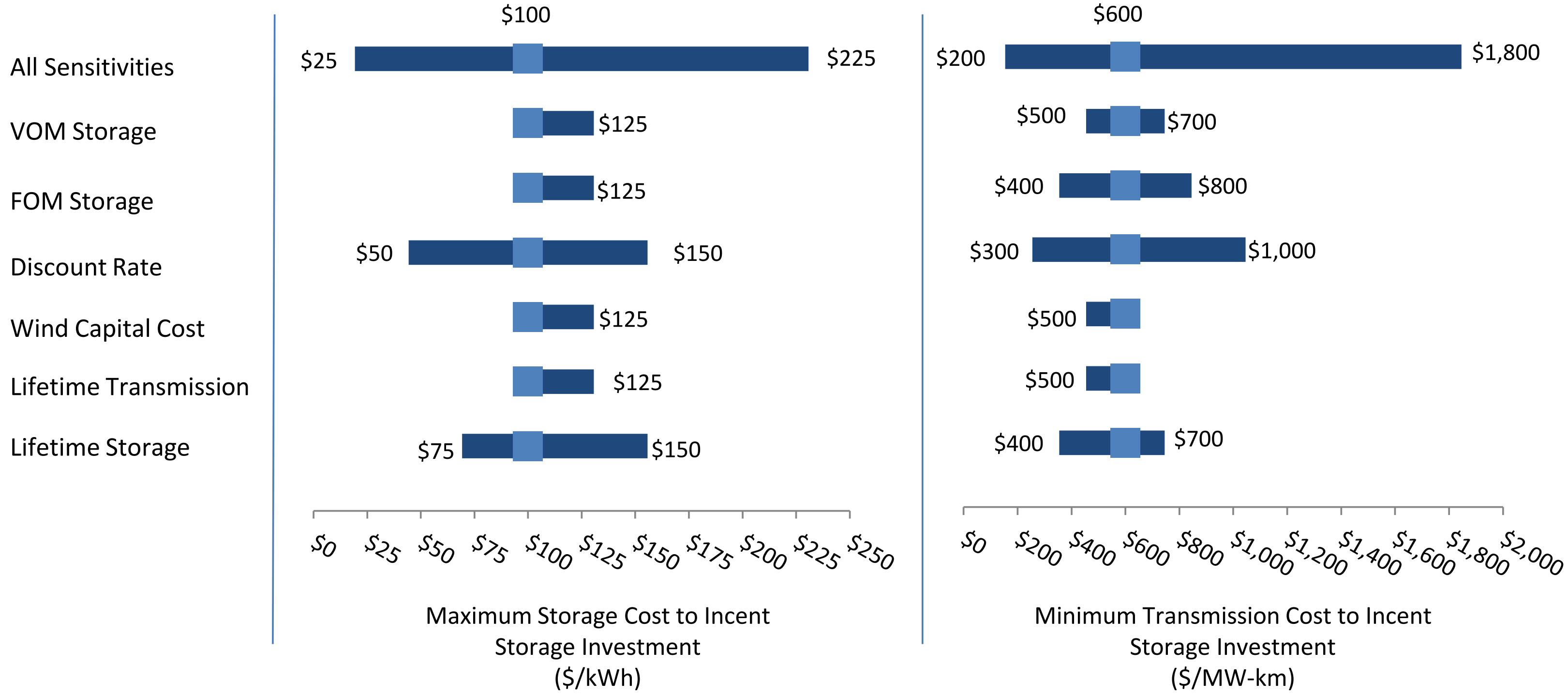
Sensitivities	Units	Low cost	Base cost	High cost
VOM storage	$/MWh	4	7	10
FOM storage	$/kW	1	2.5	4
Discount Rate	%	20%	10%	5%
Wind Capital Cost	$/kW	2,500	2,200	1,500
Lifetime Transmission	year	30	40	50
Lifetime Storage	year	20	10	7

VOM and FOM costs for storage affect its annual operation costs and therefore how competitive storage is as a replacement for transmission. Technology lifetime determines the amount of time over which the capital costs of an asset can be discounted. Lifetime, along with the discount rate, therefore affect the average cost of electricity ($/MWh) calculation. For shorter lifetime assets like storage (10 years), we assume that the investor will reinvest in the asset after its lifetime. Because storage competes with transmission, higher transmission costs make storage more economical. Transmission lifetime is therefore inversely correlated with the break-even cost of storage. Similarly, wind capital costs are inversely correlated with storage competitiveness because the wind farm is a large fraction of the overall costs. If wind costs are very high, then adding even small amounts of storage to deliver more power will decrease the average cost of electricity (ACE), and make the project more economical. Also, because storage is a smaller portion of overall costs, higher discount rates make storage more competitive since discounting more significantly affects the economics of higher cost assets such as wind and transmission.

Figure 2.6 shows the results of the sensitivity analysis. The left figure reports the maximum capital cost for energy storage that would incent some non-zero amount of storage investment (break-even cost of storage). Similarly, the right figure shows the minimum transmission cost that would make the decision-maker invest in some amount of storage (break-even cost of transmission). The figure does not report the sizes of transmission and storage at these break-even costs; Figure 2.3a-f reports these values for base case assumptions.

The lower bounds for VOM and FOM costs do not change the break-even cost for storage. These costs do however affect the break-even cost of transmission. The lower bounds for wind capital costs also don't affect the results. Transmission lifetime of 50 years also doesn't affect storage competitiveness because the difference between 40 and 50 years for discounting is trivial.

With all sensitivities included, the break-even capital cost of storage to incent storage investment ranges from \$25 to \$225/kWh, with a best estimate of \$100/kWh. Similarly, the break-even capital cost of transmission ranges from \$200 to \$1,800/MW-km, with a best estimate of \$600/MW-km.



VOM = variable operation and management, FOM = fixed operation and management

Figure 2.6: Tornado diagrams showing the sensitivity of results to key input assumptions. The figures show the maximum storage cost and minimum transmission cost for storage investment to be nonzero. Blue squares represent results from the base case assumptions made in Table 2.3. Detailed results of the base case are available in Figure 2.3a-f. Low and high cost assumptions represent best and worst cases for storage, respectively. Because storage competes with transmission, any assumption that makes transmission more expensive allows storage to become more competitive.

2.5 Discussion

Storage might have a role in replacing transmission when integrating remote wind resources, but capital costs need to be less than $100/kWh and transmission costs need to be greater than or equal to $600/MW-km. Current storage costs are highly uncertain, but roughly 3 to 10 times higher than $100/kWh for lithium-ion batteries and 5 times higher for sodium-sulfur batteries. Of the costs shown in Table 2.2, only the optimistic cost estimates for CAES and used Li-ion batteries could meet this cost target. Further, our analysis of this application of energy storage assumes perfect foresight in hourly wind power for three days, which is a very optimistic assumption. It is likely that the true break-even cost of storage used as a replacement for transmission is even lower since errors in forecasting will result in suboptimal storage decisions and therefore make the storage asset less valuable.

Further, even if storage capacity was ample and free, a minimum amount of new transmission capacity must be built to deliver power. We show that the transmission capacity that is most economical ranges from 72% to 95% of the installed wind capacity across all cost scenarios. This range is consistent with previous literature (Pattanariyankool and Lave, 2010).

Although it's unclear what transmission costs would actually be in accessing this farm, beyond a certain cost threshold, the project would not be profitable. If for example, an independent power producer could negotiate a guaranteed rate of $80/MWh (ignoring subsidies), transmission costs would need to be lower than $400/MW-km to make investing in the remote farm worthwhile. Because storage is only economic when transmission costs are beyond $600/MW-km, in this scenario, it is unlikely that storage would be used as a replacement for transmission capacity.

The addition of a production tax credit, which is currently $22/MWh, as well as renewable energy credits, which previously have been up to $20/MWh for wind generation in Illinois, might make this remote project economical even at higher capital costs. However, investors would have to manage the uncertainty in the future regulatory environment when relying on these subsidies. Our analysis provides a benchmark cost estimate with which decision-makers could use to value the profitability of such a project when considering all these factors.

The main drawback of using energy storage as proposed in this chapter is that the incremental percent increase in power delivered from storage is far less than an incremental percent increase in transmission. Since we assume that the value of electricity is the same in each hour, one of the main advantages of energy storage, its ability to control when power is delivered, is eliminated. It may be that using energy storage for other applications, such as providing frequency and voltage control, would generate more value; we do not account for such effects. Another possible scenario to model would be to allow the storage device to simultaneously participate in ancillary markets in the North Dakota energy markets as well as deliver power to Illinois. This optionality would increase the value of storage significantly and therefore increase its break-even value to greater than $100/kWh. Further, this analysis did not consider the use of existing transmission lines. It is possible that wind farms that are transmission-constrained by existing transmission could avoid curtailment without having to build new transmission capacity. However, given the problem framework that we've defined, those interested in accessing remote wind resources today are likely better off by building only transmission capacity and not energy storage. Energy storage is likely better suited for providing other services when it is not co-located with a remote wind farm.

Chapter 3

3 Economic tradeoffs of where to site new wind farms in the Midwest

This work has already been published in *Energy Policy* as the reference below. The chapter uses "we" instead of "I" to reflect the contributions of my co-authors.

> *Lamy, Julian, Paulina Jaramillo, Inês Azevedo, and Ryan Wiser. "Should We Build Wind Farms close to Load or Invest in Transmission to Access Better Wind Resources in Remote Areas? A Case Study in the MISO Region." Energy Policy 96 (September 2016): 341–50.*(Lamy et al., 2016)

3.1 Introduction

Replacing conventional generation with wind power could reduce greenhouse gas (GHG) emissions and provide a sustainable, low-carbon source of energy. However, deciding where to build wind farms is not trivial. Many of the highest quality onshore wind resources in the United State (U.S.) are located in the Midwest, often in areas that are far away from load centers and that therefore require large transmission investments. An alternative to accessing these distant resources is to build farms closer to electricity consumers where wind power output may not be as high, but less transmission investment is needed. This chapter provides a modeling framework that policymakers can use to inform where to build wind farms given these tradeoffs.

We focus on the Midwestern electricity grid, MISO (Midcontinent Independent System Operator), which spans 15 states. In 2012, 21% of total electricity sales were within Illinois, the most populous state in MISO. Including sales in the neighboring states of Missouri and Indiana, this percentage increases to

49%. In contrast, states that are more remote from major load centers such as North and South Dakota collectively account for only 4% of MISO's electricity sales[2](U.S. Energy Information Administration, 2012). Compared to wind farms in North Dakota, Illinois wind farms tend to have lower transmission interconnection costs, as there is already a robust network of existing infrastructure (high voltage lines, substations, etc.). Based on data gathered from MISO's transmission interconnection queue, median transmission upgrade costs for new wind farms in Illinois are about $33/kilowatt (kW) of installed wind capacity, compared to $762/kW in North Dakota (see Table 3.1 in Section 3.2 for more details). This does not mean that North Dakota wind farms need to build dedicated, long-distance transmission lines into major load centers in Illinois, but it is likely more costly to upgrade the more limited transmission infrastructure in North Dakota compared to Illinois.

There may be benefits to building wind farms in remote areas if the total amount of power produced is larger than in closer locations and if it is produced at times when the electricity generated is more valuable. Consider again the example of North and South Dakota compared to Illinois. According to power output data of hypothetical wind farms from the National Renewable Energy Laboratory (NREL), North and South Dakota wind farms result in average capacity factors of 43% compared to 40% in Illinois (EWITS, 2012). At first glance this difference may appear small, but it accounts for a cost difference of $1.4 billion in upfront costs when trying to meet a wind generation target of 40 terawatt-hours (TWh) per year (equivalent to renewable targets in MISO), assuming that installed capital cost for wind farms are $1,750/kW. Accessing higher capacity factor wind sites in remote areas could substantially reduce costs to meet policy goals, even if transmission upgrade costs for these sites are higher. Furthermore, the timing of wind power production is critical. Wind farms are most valuable when they produce during times of high energy demand, which corresponds to higher prices in energy markets, and a larger payment in capacity markets (in MISO, capacity payments for wind farms are based on the capacity factor of wind

[2] For simplicity, we used total electricity sales within each state that is in MISO, even though some states are only partially in MISO. We did not include states within MISO's Southern region since they are outside the scope of our study's geographical focus.

farms during peak load hours (MISO, 2013a)). Additionally, because wind power production is variable, other generators will have to ramp to fill in the gaps when wind speeds are low. Wind farms that require less ramping from other generators are therefore more valuable. Thus, when considering the temporal aspects of wind power, the problem of where to site wind farms (remote or local locations) becomes much less trivial than simply comparing capacity factors and transmission costs.

Hoppock and Patiño-Echeverri (2010) introduced a wind capacity expansion model to meet 10 TWh of new wind generation in MISO. They accounted for annual energy production at different wind farms as well as the transmission cost to access farms in distant locations such as Minnesota and Iowa. They find that given the high transmission cost to access more distant locations, it’s more economical to build near lower-quality wind resources in Illinois. However, the authors also acknowledge that results depend on their transmission cost assumptions, which are based on limited data and may not reflect future costs. The transmission landscape is rapidly changing in the region, as demonstrated by the Multi Value Project portfolio, a $6.5 billion initiative that will increase transmission interconnectivity throughout MISO (MISO, 2012a). Therefore, as Hoppock and Patiño-Echeverri (2010) point out, it’s very difficult to make static assumptions about transmission costs and arrive at strong conclusions.

Ultimately, the decision to build wind farms in a remote region depends on the difference in transmission upgrade costs between regions. In this study, we estimate the difference in transmission upgrade costs needed to justify the decision to site wind farms in lower-quality sites that are closer to load. We refer to this as the “break-even transmission cost premium” to access remote wind farms. If the difference in transmission costs across regions is below the break-even value, then it is more economical to build wind capacity in the remote region. We do not make strict assumptions about transmission costs, and instead provide break-even cost premium values that can be used by decision makers with information on true transmission costs. No paper to date has used this approach when considering siting decisions for wind development.

We use MISO as a case study given its ambitious renewable goals. We denote Illinois as the "local" region and Iowa/Minnesota (MN-IA) or North/South Dakota (ND-SD) as the "remote" regions. We assume that new wind capacity must be built in either the local or remote region (or both) to meet 40 TWh per year of additional wind generation in MISO. This goal is equivalent to complying with the Renewable Portfolio Standards (RPS) in Illinois, Minnesota, and Missouri[3]. These 40 TWh of wind generation correspond to about 5.7% of total load in MISO. There is currently about 40 TWh of existing wind in MISO so with the additional wind built in our analysis, this percentage would increase to 11.6% [(MISO, 2015a), (MISO, 2015b)]. We develop an optimization model that minimizes total wind installation and transmission costs to meet this target by selecting among a predetermined set of hypothetical wind farms. We account for each wind farm's energy value, capacity value, and the negative effects to dispatchable generators due to the variability in power output from the selected wind farms. No paper to date has included these temporal aspects of wind power production within a wind capacity expansion model. Finally, to calculate the "break-even transmission cost premium" to build wind farms in remote regions, we parameterize our transmission cost assumptions across different scenarios to see how the optimal solution changes (i.e., whether wind farms are built in Illinois versus MN-IA or ND-SD). We test how different assumptions affect these values in a comprehensive sensitivity analysis in Section 3.3.3.

This work contributes to the wind integration literature by presenting a conceptual framework for analyzing wind farm siting tradeoffs, and the numerical results reported here are meant as an approximation to study these tradeoffs in MISO. To demonstrate the usefulness of these results, we compare our estimates of "break-even transmission cost premiums" to historical transmission cost premiums in MISO. The work we present here is generalizable and could be fitted to data from other locations with strong remote wind areas such as Western vs. Eastern China or Northern Scotland vs. the rest of the United Kingdom. The computational time for the model developed for this analysis is less than

[3]RPS Targets (DSIRE, 2015) were compared to wind generation by state (U.S. Energy Information Administration, 2015) to estimate additionally required wind generation.

5 minutes and can be expanded upon and tested under multiple assumptions without introducing much computational complexity.

3.2 Methods and Data

This analysis relies on a mixed-integer optimization model that minimizes annual costs and selects which wind farms to build, among a predetermined sample, in order to meet a specific annual wind generation target. The decision to build a farm is modeled with decision variable b_k that takes the value of 1 if the wind farm k is built, 0 otherwise. Total annual costs to meet the target are the difference between costs and revenues from the selected wind farms. On the costs side, we include the wind farm annualized installation costs ($WCost_k$ [in \$/MW]), the fixed operation and maintenance costs ($OMCost_k$ [in \$/MW]), and the annualized transmission upgrade costs ($TCost_k$ [in \$/MW]). Each of these costs is represented per unit of nameplate capacity, and is multiplied by the plant's respective nameplate capacity ($NamePlateMW_k$ [in MW]). On the revenue side, we include capacity payments and the market value of the energy produced. The capacity payments are obtained by multiplying the capacity market price (*CapPrice* [in \$/MW]) by the percentage of capacity credit ($CapCreditPercentage_k$) and the nameplate capacity of the farm ($NamePlateMW_k$ [in MW]). The energy value, or fuel savings to generators, is the wind output at a farm k in each hour t ($wind_{t,k}$, [in MW, multiplied by one hour, resulting in MWhour – i.e., MWh]) times the marginal energy component (MEC) of market prices in that hour (MEC_t [in \$/MWh]). Lastly, we also account for the costs of wind power variability. Variability in net load (total load minus wind generation) is a measure of system-level variability induced by having increasingly variable generation in the system. It represents the amount of load that conventional, dispatchable generators have to serve. We therefore include a penalty, *NetLoadPenalty* (\$/MWh), for any change in net load (MW_t) between hours to reduce the system- level variability cost of the new wind farms. For all annualized terms, we use an 8% continuous discount rate.

$$\underset{b_k \in M}{\text{argmin}} \quad \sum_{k=1}^{M} b_k * \left(\begin{array}{c} (WCost_k + OMCost_k + TCost_k) * NamePlatekW_k \\ - CapPrice * CapCreditPercentage_k * NamePlateMW_k - \sum_{t=1}^{T} wind_{t,k} * MEC_k \end{array} \right) + \sum_{t=1}^{T} (NetLoadPenalty * |MW_t - MW_{t-1}|) \qquad (1)$$

s.t.

$$MW_t = Load_t - \sum_{k=1}^{M} (wind_{t,k} * b_k) - existingWind_t \qquad ,\forall t \in T \qquad (2)$$

$$\sum_{t=1}^{T} \sum_{k=1}^{M} (wind_{t,k} * b_k) \geq Annual\ Generation\ Target \qquad (3)$$

Equation (2) shows that in every hour, net load (MW_t [in MW]) needs to equal the total load ($Load_t$) minus the power output of new wind farms ($\sum_{k=1}^{M} (wind_{t,k} * b_k)$) and existing wind farms ($existingWind_t$). Equation (3) imposes a constraint so that there are enough wind farms to meet an annual wind generation target. For the MISO case study included in this chapter, we set this target to 40 TWh.

Wind output data. All the wind farm locations, capacity, and hourly wind power output ($wind_{t,k}$) come from the EWITS dataset created by NREL (EWITS, 2012). The EWITS dataset consists of 1,326 hypothetical wind sites in the Eastern Interconnection with an estimate for the maximum capacity of each farm and simulated wind power output from 2004 to 2006, in 10-minute increments. We use the 2006 hourly data for the 443 EWITS sites that are located in the MISO region, including North Dakota, South Dakota, Minnesota, Iowa, and Illinois. We also test how the results of this analysis change when using 2004 and 2005 data in a sensitivity analysis presented in Section 3.3.3. EWITS does not state whether existing wind farms are already operating in their simulated locations. We assume that each new farm would require 85 acres/megawatt (MW) - based on the average of 161 projects reported by Denholm et al. (2009)- and exclude farms from the EWITS dataset that are within the footprint of existing farms. We use a dataset from the U.S. Geological Survey to identify existing farm locations (U.S. Geological Survey, 2015). In the final list of potential EWITS sites - 320 in total - all individual states have enough capacity to reach a generation target of 40 TWh from wind farms, but the wind quality differs across states. We exclude wind farms in Indiana, Michigan, and Wisconsin because capacity factors of farms in these states are low compared to other states. In preliminary model scenarios, including farms in these states did not yield different results, but increased computational requirements substantially. Further, all wind farms from the EWITS dataset in Missouri are outside of the MISO region so they are excluded. Lastly, we assume that all wind farms have a transmission loss of 2.2%, which is the reported average in MISO (MISO, 2016a).

Installation and O&M costs. We assume that wind installation cost is $1,750/kW, which is the weighted average of 16 wind farms currently under construction (2 GW total) reported in Wiser and Bolinger (2014). In Section 3.3.3, we also include a sensitivity analysis of varying installation costs between $1,500/kW and $2,000/kW. We assume fixed operation and maintenance costs are $51/kW, based on the assumption for year 2014 used in the *Wind Vision Report* by the U.S. Department of Energy (2015). Finally, we assume a 20-year lifetime for each wind farm.

Transmission costs. As in Mills et al. (2009), we treat transmission costs as a function of wind farm capacity ($/kW), not distance. This assumption reflects the fact that some wind farm projects can connect to the grid infrastructure that is nearby. Even a farm in North Dakota wouldn't necessarily need to build brand new transmission lines into major load centers (i.e., all the way to Chicago) to sell power into the grid. An individual farm may indeed need to build long transmission lines while another may only need to upgrade equipment at an existing substation (no distance component). Both would incur interconnection costs, but a distance-based cost metric does not account for this difference whereas a capacity-based metric does. Furthermore, using a distance-based cost metric requires knowing the transmission line distance required for each wind project, which is very project specific and thus difficult to generalize.

To account for capacity-based transmission costs, we rely on data from MISO's transmission interconnection queue, which is publically available (MISO, 2013b), and provides details of the required transmission upgrades (mandated by MISO) for different energy projects – including wind farms – across MISO from 2003 to 2013. Table 3.1 shows statistics of transmission costs from this dataset for wind farms in the states we consider. The median cost in North and South Dakota was $600-$700/kW compared to $33/kW in Illinois. This difference is large because Illinois (containing about 25% of load in MISO) has a more robust transmission system than ND-SD (which contains about 4% of load) (U.S. Energy Information Administration, 2012). Therefore, wind farms in ND-SD typically need to build more infrastructure (new substations, new power lines, upgrades to existing power lines, etc.) to serve load in MISO compared to those in Illinois. A difference also exists between MN-IA and Illinois, although it is much smaller. Median interconnection costs in MN-IA were about $90/kW, compared to $33/kW in Illinois. Again, this does not mean that all existing wind farms in MN-IA built transmission lines directly into Illinois – it means that historically, more infrastructure was needed to reliably connect wind farms in MN-IA to the MISO grid.

Table 3.1: Historical transmission costs per state (2014 $/kW of wind capacity).

	Percentile			# Observations in dataset
	25th	50th	75th	
IL	$22	$33	$115	29
IA	$55	$95	$180	20
MN	$50	$85	$158	51
SD	$267	$622	$727	29
ND	$264	$762	$1,117	39

In the most recent queue database (MISO, 2013b) there were 338 wind farms with publically available transmission cost estimates in the states analyzed in this work. Observations that recorded $0/kW in upgrades were excluded since these cases were for smaller projects and don't reflect the costs necessary to comply with 40 TWh of new wind generation. Some cost calculations in the queue dataset accounted for the recent Multi-Value transmission projects (MVP) in MISO, which are designed to reduce interconnection costs in MISO (MISO, 2012a). Sufficient data (sample >20) for wind farms including MVP were only available for Iowa and Minnesota, which is not surprising since these states are the principle benefactors of the MVP projects. Thus the transmission cost estimates in this table for Iowa and Minnesota are derived from the subset of observations that included MVP projects (71 total); the other state cost estimates are derived from both MVP and non-MVP observations inclusive (97 total). The final dataset includes 168 different cost estimates (adjusted to 2014 $) from projects proposed between 2003 and 2013.

For the MISO case study included in this chapter, we do not make strict assumptions about transmission costs in different states. Instead, we aim to identify how much more expensive (in $/kW) would transmission costs in the remote area have to be so that it never makes economic sense to build wind farms anywhere except Illinois (closest to load). To do this, we construct scenarios with increasingly higher incremental transmission costs between remote states (MN-IA and ND-SD) and local areas (Illinois) and report when the most economical solution is to build farms only within Illinois. We range the transmission cost difference between regions by $0 to $1,000/kW, in $10 increments, and refer to this difference as the "transmission cost premium". When this cost premium is $0/kW, farms in remote regions with better wind resources are favored. As the difference increases, and transmission costs are higher in remote regions, more farms in Illinois are favored. The break-even transmission cost premium is the cost differential where the solution changes from some non-zero capacity built in remote regions to 100% of capacity built in Illinois. Figure 3.1 summarizes how we treat transmission costs in our model. We group Iowa and Minnesota together (MN-IA) as well as North and South Dakota (ND-SD) since transmission costs in these states were historically similar (see Table 3.1).

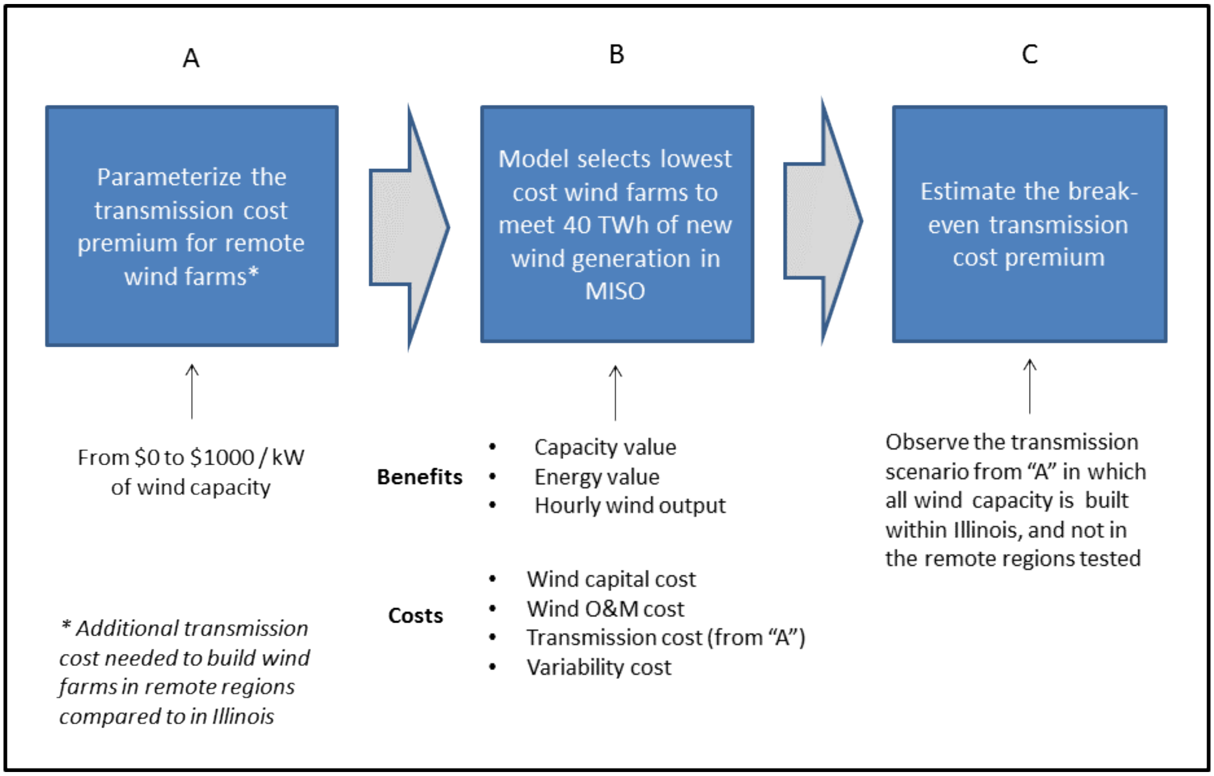


Figure 3.1: Summary of modeling method to estimate the break even transmission cost premium to access remote wind farms.

Marginal Energy Component (MEC). We use market price data to estimate energy value of wind power in each hour. Locational Marginal Prices (LMP) provide an approximation of the cost reductions that may result from adding a zero marginal cost resource like wind, as well as the temporal value of wind power (Fripp and Wiser, 2008; Lewis, 2010). However, LMPs vary by price node (there are thousands of nodes across MISO) since they incorporate transmission congestion and can therefore be extremely volatile due to the sudden occurrence of congestion on the grid. MISO also publishes data on the marginal energy component of prices (MEC) per hour, which is the energy-only component of market prices that represents the marginal cost generation for meeting load across MISO. MEC is by definition uniform across the MISO territory since it does not include the cost of transmission congestion, which is internalized in LMPs. In this analysis, the energy value calculation relies on this MEC and strictly reflects the value that different wind farms offer in reducing the marginal costs (effectively the short-term fuel costs) of existing generators.

We present three additional scenarios in Section 3.3.3 to test the robustness of the energy value calculation. The first uses LMPs at different price hubs instead of MEC. The second uses the marginal costs of coal and gas generators (estimated using a simple dispatch model) to estimate energy value. Additionally, there is some indication that market prices (and thus energy value) may decline with increasing levels of wind capacity additions (Hirth, 2013; Mills and Wiser, 2014). This reduction effect is not endogenous in our model. Therefore, we also include a scenario that explores how results would change under lower market prices. Our conclusions are robust to these sensitivities.

Capacity prices. We assume that capacity prices are equal to $150/MW-day. Our model assumes that wind farms will have an effective lifetime of 20 years, which means that the capacity price assumption should represent the expected average price over this timeframe. MISO procures capacity only two months ahead, as opposed to the neighboring grid (PJM, Pennsylvania, Jersey, Maryland Power Pool), which procures capacity three years ahead. Many attribute the large difference in capacity prices between these regions to this difference in procurement timeframe (Constellation, 2014). For example, in the 2014-2015 planning year, capacity prices in MISO ranged from $3.29 - 16.75/MW-day compared to $128-172/MW-day in PJM (MISO, 2014; PJM, 2014). Some argue that if MISO operated liked PJM by procuring capacity 3 years ahead, then MISO's capacity prices would be closer to those in PJM (Constellation, 2014). Furthermore, capacity prices in Illinois (where most load is in MISO, and where there are interconnections with PJM) are increasing and converging to those in PJM. In the 2015-2016 planning year, the MISO capacity price in Zone 4 (Illinois) was $150/MW-day, compared to $134/MW-day in PJM's Illinois zone (ComEd) (MISO, 2015c; PJM, 2015). Moreover, a capacity price of $150/MW-day is the midpoint between the lowest MISO capacity price in the 2014-2015 planning year ($16.75/MW-day) and the absolute maximum price that one might observe in the market (~$300 / MW-day which is equivalent to the cost to build a new natural gas plant)[4]. $150/MW-day reflects a reasonable

[4] Assuming $13.17/kW-yr in fixed overhead costs and $917/kW in overnight capital costs, annualized over 20 years with an 8% discount rate (U.S. Energy Information Administration, 2014).

"base case" value between the possible extremes. Finally, in Section 3.3.3 we include a sensitivity analysis that relies on a lower capacity price ($17/MW-day) and show that our conclusions are robust to this sensitivity.

Capacity credits. We use the same method as MISO's to calculate wind capacity credits (the percentage of installed wind capacity that receives capacity payments) by first calculating the capacity factor for each wind farm (320 total) for the top 8 peak load hours of 2014 ($Load_k$). These capacity factors are then multiplied by a scalar of K=0.65, which represents MISO's ratio of effective load carrying capacity (ELCC) to the weighted average of wind farm capacity factors during peak hours[5]. The result is a capacity credit percentage that ranges from 3% to 26%, with an average of 11%. For comparison, in the 2014-2015 planning year in MISO, the system-wide average wind capacity credit percentage was 12% (17.39% capacity factor at peak load hours multiplied by K=0.7) (MISO, 2013a).

Variability costs. Apt (2007) shows that most of wind variability occurs across a frequency of hours and slow-ramping conventional generators, such as coal and gas-fired power plants, can balance the variability. This inter-hour variability, however, creates an added cost to conventional generators that must ramp under suboptimal conditions. For example, in their model of PJM, Oates and Jaramillo (2013) show that increasing wind generation to 20% increases coal startup costs. Balancing the variability of wind could increase the need to maintain increased reserves, which would also increase costs (Mauch et al., 2013). Our model captures this increased cost of variability at an hourly scale.

One common approach used to estimate variability costs is what DeMeo et al. (2005) refer to as "cost of service studies", which is the cost of serving the portion of system load not served by wind (i.e., net load). As wind increases, conventional generators may have to ramp up and down more regularly to respond to the variability in wind power (which can't be dispatched), and therefore the dispatchable generators incur

[5] This analysis uses value K=0.65, which is the average of the last two planning years ((MISO, 2012b), (MISO, 2013a))

higher costs. On the other hand, some of the variability may coincide with variability in load, thus providing a benefit to the grid. In order to capture the potentially mixed effects of variable wind output, studies increasingly rely on net load to evaluate grid integration issues (see for example Fertig et al. (2012) and Mauch et al. (2013)). Using dispatch models of all generators in a system and comparing operation costs with and without new wind power, it is possible to estimate the net change in the costs of dispatching power plants and divide by total increased wind generation to arrive at variability costs measured in $/MWh. To evaluate these variability costs, DeMeo et al. (2005) perform a meta-analysis of different studies that calculated the effect of wind variability and uncertainty on grid operation costs. They find that studies' total costs range from $2 - $5/MWh of wind energy. Wiser and Bolinger (2014) show similar integration costs (some including both variability and transmission costs) for more recent studies.

We are interested in measuring the relative difference in variability impacts across different farms that can be selected, not an exact measure of variability costs due to wind power penetration. Therefore, we rely on a modeling approach that provides a functional approximation of the relative difference in variability costs across farms, since all farms are subject to the same assumptions. We choose this approach to help reduce model complexity, reduce computational time, and increase our model's generalizability to other regions. To penalize net load variability, we rely on 2014 load data for MISO (MISO, 2015b) and assume a penalty of $10/ MWh for each hourly change in net load. This number is equal to the average ancillary service price in MISO in 2014, which we use as a proxy for this penalty (MISO, 2015d). In Section 3.3.3, we also include a sensitivity analysis to test whether lower ($5/ MWh) and higher ($20/MWh) net load variability cost assumptions affect the results of this analysis and find that results change by less than 10%.

This approach for modeling variability cost is a simplification of the models described in DeMeo et al. (2005) since we don't directly measure the additional cost to generators resulting from net load variability across time. Instead, we use a proxy of $10 for each hourly change in net load. Nonetheless, we arrive at costs that are within a reasonable margin of error of past studies. We estimate that total variability costs in our model (using $10/MWh net load penalty) are about $5/ MWh of total wind generation (~$200 million for 40 TWh of wind per year).

We do not include the option to build grid-level energy storage, which has been shown to reduce hourly variability effects on the grid and decrease transmission costs to access remote wind farms. Past research has shown that, in MISO, this application of energy storage is uneconomic for realistic technology solutions (grid batteries and compressed-air-energy-storage - CAES - facilities) at current as well as projected costs (see Chapter 2). Low natural gas prices have further hindered the development of storage projects, in particular CAES, as noted in Schulte et al. (2012).

Assumption summary. Table 3.2 lists all our base case assumptions. Section 3.3.3 also includes a sensitivity analysis to several of these assumptions, noted with "**" in Table 3.2. We solve the model using CPLEX in GAMS v23.6.

Table 3.2: Base case model assumptions.

	Base Case	**Source**
Wind capital costs ($/kW)	$1,750**	(Wiser and Bolinger, 2014)
Fixed O&M ($/kW-year)	$51	(EIA, 2015)
Transmission capital costs ($/kW of wind)	Parameterized	
Wind farm lifetime (years)	20	(Tegen et al., 2012)
Transmission lifetime (years)	40	
Discount rate (%)	8%	(Wiser and Bolinger, 2014)
Hourly wind output	2006 EWITS**	(EWITS, 2012)
Hourly energy value	2014 MCE**	(MISO, 2015e)
Hourly load	2014 MISO	(MISO, 2015b)
Hourly existing wind generation	2014 MISO	(MISO, 2015a)
Capacity Price ($/MW-day)	$150**	
Capacity Credit Percentage	Varies by farm, based on MISO's method	(MISO, 2013a)
Net load Penalty ($/MWh)	$10**	Based on average market price for operating reserves in MISO in 2014 (MISO, 2015d)

** Sensitivities to these assumptions are presented in Section 3.3.3

3.3 Results and Discussion

3.3.1 Break-even transmission costs to access remote regions

Figure 3.2 shows the tradeoff between transmission costs to access remote regions, and the benefits of accessing high quality wind resources in those areas. Figure 3.2A highlights the trade-offs between building wind in Minnesota and Iowa (MN-IA) versus in Illinois, whereas Figure 3.2B shows the trade-offs of building wind in North or South Dakota (ND-SD) versus in Illinois. The horizontal axis varies the assumed incremental transmission cost (or "transmission cost premium") of building wind farms remotely instead of locally, represented in \$/kW of installed wind. The vertical axis shows the percentage of total capacity built in each state under the least cost optimization defined in equations 1 to 3 in Section 3.2 to meet 40 TWh of new wind generation in MISO. The lines in Figure 3.2 are not smooth and move in steps depending on the transmission cost scenario because of the integer nature of the solution.

A **B**

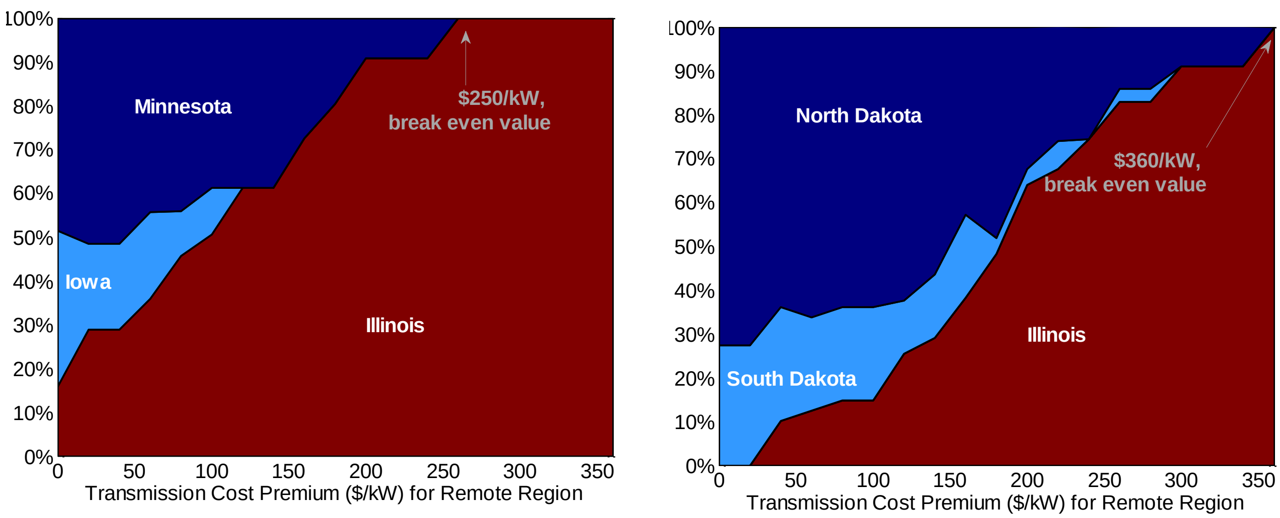


Figure 3.2: Model results showing the % of capacity built in each state when varying transmission costs between remote states and Illinois (\$/kW of wind capacity).

The total capacity built across the different scenarios ranges from 10.5 to 11.2 GW. As noted in Figure 3.2A, if there is no transmission cost premium for MN-IA wind farms, then the least cost solution is to build most wind farms in MN-IA (84% of 10.8 GW) given their better wind resources. Between $0 and $250/kW, between 0% and 84% of capacity is built in MN-IA. Once the cost premium reaches $250/kW, not even the locations with the best wind resources in MN-IA are selected; instead, the least cost solution is to build all capacity within Illinois (11.2 GW). When transmission costs are the same in Illinois and in MN-IA, the least cost solution still includes some Illinois wind farms (1.7 GW) that have comparable capacity factors than those in MN-IA. Figure 3.2B illustrates similar results for the decision to build in ND-SD or in Illinois. When there is no cost premium, the least-cost solution is to build 100% of the needed capacity in ND-SD. Once the cost premium reaches $360/kW, the least cost solution is to build all capacity within Illinois (11.2 GW). Therefore, $250/kW and $360/kW represent the break-even transmission cost premiums to build in MN-IA or ND-SD versus Illinois.

One way to better understand the meaning of these break-even values is to compare them to historical transmission upgrade costs. For example, as noted in Table 3.1 in Section 3.2, the median of historical transmission upgrade costs for wind farms in MN-IA was about $50/kW more costly than in Illinois ($85-95 compared to $33). This is well below the estimated break-even cost premium of $250/kW. We therefore expect that building wind farms in MN-IA is more economical than in Illinois. In fact, given the median of historical costs, the results in Figure 3.2A suggest that it's best to build about 70% of all wind capacity in MN-IA, and the rest in Illinois (when x-axis = $50/kW). Under the same conditions, if decision-makers decided instead to build every wind farm in Illinois (100% instead of 30%), total costs would be higher by about $50 million per year, or $500 million over the lifetime of the wind projects (discounted at 8% over 20 years). The opposite result holds for ND-SD when comparing the estimated break-even values to historical transmission costs. Although North and South Dakota have some of the best wind resources in MISO, the required transmission costs to access wind farms in these states could only be up to $360/kW more costly than in Illinois to incentivize development. Historically the difference in transmission costs between the Dakotas and Illinois have been about double this break-even value.

These conclusions are meant as an approximation based on a comparison between historical transmission costs and the break-even values estimated for this chapter. Our main contribution is in providing estimates of the break-even cost premiums, which can help decision-makers choose optimal siting locations given their information on transmission costs for specific projects.

3.3.2 Driving factors for optimal decisions

Table 3.3 shows the different value and cost components that contribute to the solutions presented in Figure 3.2. Overall, if transmission costs are the same across all states, building wind farms in remote sites can reduce the cost of meeting renewable energy targets. Most of the benefits of accessing wind resources in remote regions come from building farms with higher capacity factors, which yield lower wind installation and O&M costs, the largest costs in all scenarios. Total costs to install and operate wind farms range from $2.4 to $2.6 billion per year ($58 to $65/MWh when normalized by wind generation, which is consistent with estimates reported in Lazard's Levelized Cost of Energy Analysis (2014)). The weighted average capacity factor for farms selected in the "MN-IA" and "ND-SD" solutions are 44.5% and 45.7%, respectively, compared to 42.9% in the "Illinois" solution. This difference yields a reduction in installation and O&M costs of $95 and $163 million per year, respectively (Table 3.3). There are also improvements in energy value of wind totaling $23 and $43 million per year, respectively, due to the higher correlation between MEC and wind production for farms selected in the "MN-IA" and "ND-SD" solutions. Surprisingly, capacity value is higher for farms in Illinois, which slightly reduces the benefits of accessing remote regions. For example, without including capacity value in the model, total benefits of building farms in MN-IA and ND-SD would be overstated by about 25%. Lastly, wind farms in MN-IA and ND-SD benefit from slightly lower net load cost (i.e., there is less net load variability), resulting in $6 to $8 million per year in savings compared to the "Illinois" solution (Table 3.3).

Table 3.3: Value (cost) of select model solutions presented in Figure 3.2 ($ M/year) when assuming that transmission costs are the same across states.

Model solution	MN - IA [1]	ND - SD [2]	Illinois [3]	Difference from "Illinois" solution: MN - IA	Difference from "Illinois" solution: ND - SD
Energy Value	$1,572	$1,592	$1,549	**$23**	**$43**
Capacity Value	$83	$67	$113	**($30)**	**($46)**
Wind Installed + O&M Cost	($2,517)	($2,449)	($2,611)	**$95**	**$163**
Net Load Penalty Cost	($194)	($192)	($200)	**$6**	**$8**
Net Cost	($1,056)	($982)	($1,150)	**$94**	**$168**

1) $0/kW in Figure 3.2A, 2) $0/KW in Figure 3.2B, 3) $360/KW in Figure 3.2A and B

3.3.3 Sensitivity Analysis

Figure 3.3 summarizes a sensitivity analysis we performed to test how different model assumptions affect our main results, the break-even cost premium of transmission between Illinois versus MN-IA and ND-SD. Base case results are noted in green squares, and correspond to results presented in Sections 3.3.1 and 3.3.2. Circles represent new scenarios that deviate from the assumptions described in Section 3.2. As evident from Figure 3.3, all results from the alternative scenarios yield the same conclusions when compared to historical transmission costs. The break-even transmission cost premiums of MN-IA are always higher than the median historical cost difference between MN-IA and Illinois, and those of ND-SD are always lower than the median historical cost difference between ND-SD and Illinois.

Table **S1** in Section SI3 of the Supporting Information (SI) provides more information about these alternative scenarios.

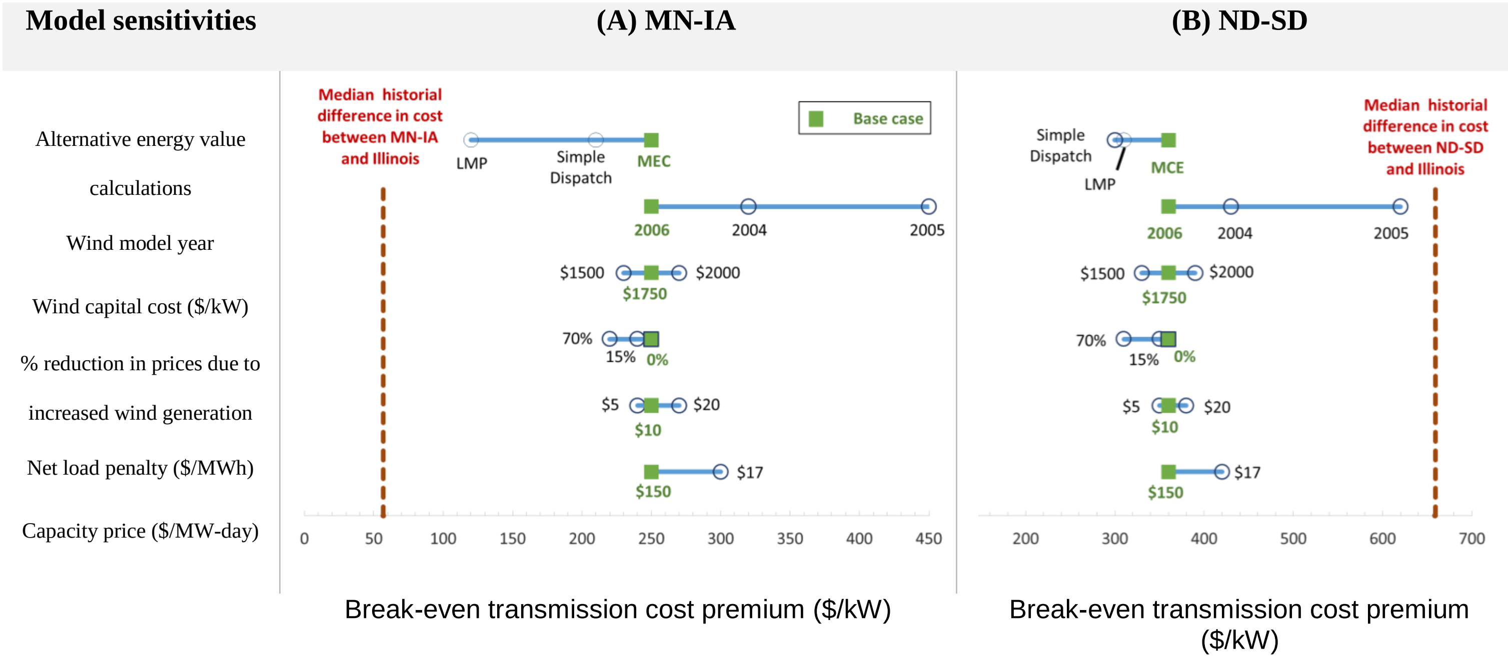


Figure 3.3: Tornado diagrams showing the resulting break-even transmission cost premium in MN-IA (left) and ND-SD (right) when using different model assumptions. Green squares represent our base case assumptions. The red dashed lines show how results compare to median historical difference in transmission costs between the remote region and Illinois.

3.4 Conclusions and Policy Implications

The lack of transmission infrastructure, or perceived high transmission costs, should not necessarily be the reason to dismiss wind projects in remote areas with high wind resources. It's important to consider the overall system net benefits of the potential siting locations. Knowing these benefits might reveal that it's worth investing in the transmission infrastructure to access them. This chapter presents a computationally efficient optimization model that can be used to estimate net benefits and calculate the break-even transmission cost premium needed to access remote areas in MISO. Future transmission costs are highly uncertain, and therefore we treat them parametrically, providing a decision-space that decision-makers with better cost information can populate to identify the optimal siting decision. We also show that the temporal value of the wind power has to be included in a wind capacity expansion model. For example, we find that excluding capacity value of wind farms (which depends on when wind farms produce energy) could misrepresent the benefits of building certain farms by 25%.

This analysis also provides insights about tradeoffs between wind resource quality and transmission costs in MISO. The results suggest that accessing windy areas in states like Minnesota and Iowa, compared to building wind farms in Illinois, provides a lower-cost option to meeting a wind energy target of 40 TWh per year in MISO. In fact, the total costs of meeting this target with wind farms in Iowa and Minnesota could be $1 billion lower than relying on wind farms in Illinois, if transmissions costs are ignored. However, once the transmission cost premium to build a wind farm in Minnesota and Iowa reaches $250/kW or above, the best strategy is to build 100% of the capacity in Illinois. Similarly, the break-even transmission cost premium to access North and South Dakota is $360/kW.

The break-even transmission cost premiums reported in this work may enable project developers and policy makers to evaluate the economic worth of transmission projects in MISO. Consider for example the Rock Island Clean Line, a 3.5 GW high voltage DC transmission line being planned from Iowa to Illinois and states further East. This project is expected to cost approximately $2 billion (Clean Line

Energy Partners, 2015), or about \$570/kW of installed wind capacity. This results in a transmission cost premium for MN-IA wind farms of \$537/kW (given that transmission costs in Illinois are \$33/kW, the historical median). This cost premium is about double our estimated break-even value for MN-IA, suggesting that it's more economical to build wind farms in Illinois rather than building the Rock Island Clean Line to access MN-IA farms. There may be other factors not considered in this work that justify building this line, such as the feasibility of siting certain wind projects or transmission lines over others, permitting issues, or the benefits of reducing transmission congestion across price nodes in MISO. Nonetheless, our findings provide a first-order approximation of the benefits of the Rock Island project, and other transmission projects like it.

The method and model developed in this chapter could be generalized to other areas in the world. For example, wind power in China shares a similar geographical trend than in the Midwest. China's most abundant wind resources are located in the Northwest, whereas most demand is located in the East (Liu and Kokko, 2010). Past research suggested that lack of transmission capacity has hindered wind development, and even limited the use of existing wind farms in China (Wu et al., 2014). It would therefore be useful to estimate the break-even transmission cost premium that would justify accessing resource-abundant regions. Our modeling framework could also be applied to assessing the economic break-even cost of building offshore wind farms versus onshore ones. Such an analysis may help policymakers justify investments in offshore wind development.

Finally, we note that other aspects, such as public acceptability, effects on local economies (such as direct and indirect job creation) will also determine decisions about where to site wind projects. While these aspects are outside the scope of this study, they certainly deserve attention.

Chapter 4

4 Interviews to understand attitudes towards wind energy projects in coastal Massachusetts communities

This work is being prepared for submission to a journal as the reference below. The chapter uses “we” instead of “I” to reflect the contributions of my co-authors.

> *Lamy, Julian V., Inês Azevedo, Wändi Bruine de Bruin, and Granger Morgan. “Interviews to Understand Attitudes Towards Wind Energy Projects in Coastal Massachusetts Communities.” Working Paper, August 2016.*

4.1 Introduction

Wind energy will likely play a key role towards decarbonizing the United States (U.S.) electricity system. Many states have already set ambitious goals in the form of Renewable Portfolio Standards (RPS) that require minimum levels of electricity demand to be met from renewable resources, like wind projects (DSIRE, 2015). Federal climate change policies may further encourage the implementation of renewable energy, such as the Clean Power Plan from the U.S. Environmental Protection Agency (EPA, 2016). Overall there is strong general approval for projects across the U.S., with 70% of Americans agreeing that more emphasis should be placed on producing domestic energy from wind resources (Gallop, 2016). However, support from communities where projects are located may be different. Past work has shown a disconnect between general support for wind power, and opposition to it in local communities where projects are located (Devine-Wright, 2005a; Van der Horst, 2007; Wolsink, 2000). This phenomenon is often referred to as not-in-my-backyard, or NIMBY. But, as many studies have pointed out, NIMBY is often too simplistic to explain opposition since it is often entangled with other more concrete factors such as visual changes to the landscape, noise from the project, wildlife impacts, or perceived inefficiencies of the technology (Wolsink, 2000).

In this chapter, we use semi-structured interviews to identify the specific characteristics that drive positive or negative opinions of wind projects within local communities. We focus on a coastal communities in Massachusetts, a State which has committed to building 2,000 megawatts of wind capacity by 2020 (2015) relative to only 100 MW installed today (U.S. Geological Survey, 2015), and thus will face a substantial increase in wind projects in the near-term. Future projects will likely include both onshore and offshore locations, a characteristic that has been shown to affect preferences (Ek and Persson, 2014; Ladenburg, 2008). Offshore projects in Massachusetts in particular have provoked significant controversy. Cape Wind, a notorious 130 turbine offshore wind project proposed in Nantucket Sound, recently failed to gain public approval due to local opposition (McNamara, 2015). We are therefore interested in exploring how preferences for offshore projects compare to those for onshore ones in coastal communities. We selected our sample from the coastal city of Gloucester, Massachusetts, which recently built three onshore wind turbines, and the neighboring town of Rockport, which is 5 miles away and also by the ocean.

The rest of this chapter is organized as follows: in Section 4.2, we describe our method and data collected, in Section 4.3 we present the results, and in Section 4.4 we conclude.

4.2 Methods and Data

We performed 15 semi-structured interviews from residents of Massachusetts's city of Gloucester and town of Rockport, which are located north of Boston on Cape Anne. Gloucester and Rockport are within 5 miles of each other, share similar demographics with other coastal communities in Massachusetts (see Section SI1 of the Supporting Information – i.e, SI), and are both by the ocean, which allows us to ask questions about the prospect of both offshore and onshore projects in their community. Furthermore, to understand how prior experience with wind projects could shape perceptions, we selected a community with an existing wind project, and another nearby community without one. Indeed, Gloucester already has three onshore wind turbines. The interviews lasted 30-60 minutes each, were audio recorded, and each interviewee was provided the incentive of $25 in the form of an Amazon gift card. We organized the interview into three main research questions:

What characteristics form preferences for wind projects? A "mental model" is the process of how individuals form beliefs about a specific topic. We are interested in learning the mental model of how communities think about the prospect of a new wind project, and more specifically, the characteristics of that project that shape their beliefs. To do this, we followed the mental models interview approach developed by Morgan *et al.* (2001). This approach begins by building an expert mental model based on past literature, which is then verified by experts and used to guide open-ended interviews with the sample of interest to learn how well the expert model fits individual beliefs. In this study, we instead begin with open-ended interviews of our sample since there is limited information from past literature on mental models for wind projects (Kempton et al., 2005; Wolsink, 2000). Using our interview results, we then present an "influence diagram" (see Section 4.3), which shows how different project characteristics influence beliefs. This diagram can be used in future research as the basis for an expert model. Each interview is *not* meant to make up a large sample of individual beliefs that is statistically significant. Instead, each interview aims at learning new information that was not already discussed in previous interviews. The end goal is to assemble a full list of the projects characteristics that form the full mental model of how our sample community thinks about wind projects. Therefore, at the beginning of the interview, participants were asked a series of open-ended questions about their perceptions of the existing wind project in Gloucester as well as a hypothetical new three turbine project in their community.

Specifically, we asked about a new three turbine project within 1 mile of their home, 5 miles from their home, and offshore. The average size of onshore wind projects in Massachusetts is only three turbines (U.S. Geological Survey, 2015), which is why we chose this size for all projects we present in this study. Similarly, in the next decade, developers in the U.S. will likely build small offshore projects (5 to 10 turbine) as pilots before larger-scale project development. This has been the main strategy for existing offshore projects in Europe. For example, Electricity de France (EDF) is currently building a project in Northeastern England 3 miles from shore that currently has 5 turbines but has the potential to include 10 more in the future (EDF ER, 2016). Development in the U.S. matches this trend. The Long Island Offshore Wind project proposed near New York City plans to start their first phase with 15 turbines 14 miles from shore, and then continue with over 200 turbines in the second phase (Dennis, 2016). Furthermore, the first offshore wind project in the U.S., which will be operational in October 2016, consists of only 5 turbines less than 4 miles from shore off the coast of Rhode Island (2016a). Therefore, our focus on a three turbine offshore projects is very relevant to the size of projects coastal communities will face in the near future.

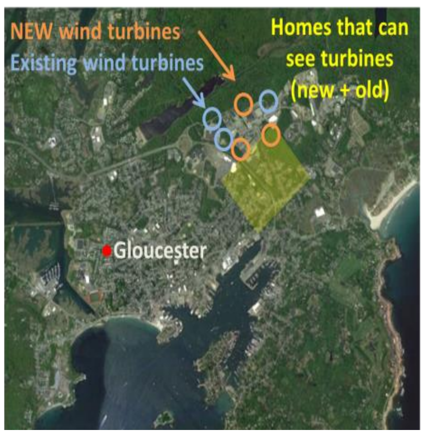
The full interview script with questions is provided in the Section SI4-C of the SI. While participants answered questions, the interviewer created a list of project characteristics that were introduced by the participant.

Which characteristics rank most important? Next, we showed the list of noted characteristics to the participant and asked if it was accurate and if they wanted to make any additions. We then asked them to rank the characteristics in importance.

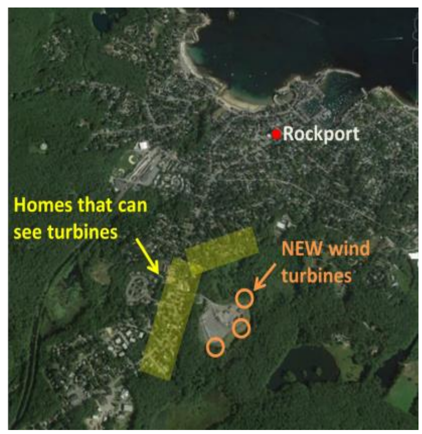
Given a set of possible projects, which one is preferred? Finally, we presented a simple discrete choice task which asked each participant to choose where to build a new wind project (3 turbines) among four alternative locations: (i) expanding on the existing wind project in Gloucester; (ii) building a new onshore project at the Rockport dump; (iii) building an offshore project 2 miles from Gloucester's shore; or (iv) building an offshore project in Rockport. We also showed a picture of what a typical offshore project looks like 2 miles from shore (see Section SI4-B of the SI). Table 4.1 reproduces the maps shown to the participants to help them make a decision among the four options. The choice task with visuals enabled us to test the relative preference of one project type over another in a more "realistic" context for specific sites in their community. In choice experiments, visual displays have been shown to improve the accuracy of learning a participant's perceptions about projects (Bishop, 2005).

Table 4.1: Screenshot of maps shown to participants in the discrete choice task.

Expansion onshore



New onshore



Offshore Gloucester

Offshore Rockport

After each interview, we transcribed and coded the conversation into the various characteristics discussed by the participant for the various projects (existing and new). Each response was coded based on the overall theme of a participant's thinking. For example, one participant said, "I think [the existing wind project] is a great idea, it helps the town, which doesn't have a lot of money." This was coded as "economics", since the participant was referring to the economic benefits their community may receive from the project. Table S3 in Section SI4-D of the SI shows all characteristics as well as example quotes of how we coded participant responses into each characteristic.

In addition to having representation from both Gloucester and Rockport, we also wanted to include participants who live near the existing 3 wind turbines in Gloucester to assess the role of prior exposure to wind projects on participants' perceptions. For those participants, recruitment was done door-to-door during the month of September 2015. The rest of the participants were recruited using posted advertisements at local stores and restaurants during the month of August 2015. The full interview questionnaire and choice tasks are presented in Section SI4-C of the SI.

4.3 Results and Analysis

In this section we characterize participants, present the main findings from the mental models approach, summarize the results from the choice task, and discuss the influence diagram we developed.

Participant demographics. As noted in Table 4.2, our sample's demographics were diverse in age, income, gender, and education. However, all participants identified with non-conservative political views (either Independent or Democrat), which is representative of political views within coastal Massachusetts communities (see Section SI4-A of the SI for more information).

Table 4.2: demographics of participants (15 total).

Demographic	Range	# Participants
Location	Rockport Gloucester <1 mile from project	4 2 9
Age	< 25 years 24-44 years 45-64 years > 65 years	3 2 7 3
Income	< $35k $35-50k $50-100 k >$100k NA	3 2 3 4 3
Gender	F M	7 8
Highest Education	High school Associates Bachelors or Masters	6 2 7
Political Affiliation	Democrat Independent Republican NA	8 6 0 1

Number of concepts to reach saturation: With 15 interviews 55 characteristics were identified (see Section SI4-D of the SI for a full list of characteristics). We stopped after 15 interviews because we observed that, after the first 10 interviews, many of the same characteristics were being repeated in each subsequent interview. Figure 4.1 shows the number of new project characteristics we learned in each interview. The first five interviews revealed 40 new characteristics, the next five revealed 10 more, and the last five revealed only 5 more. Morgan *et al.* (2001) shows that the required number of interviews to elicit the majority of concepts on a topic ranges between 10 and 20, which is why we felt confident that we learned the majority of characteristics after 15 interviews.

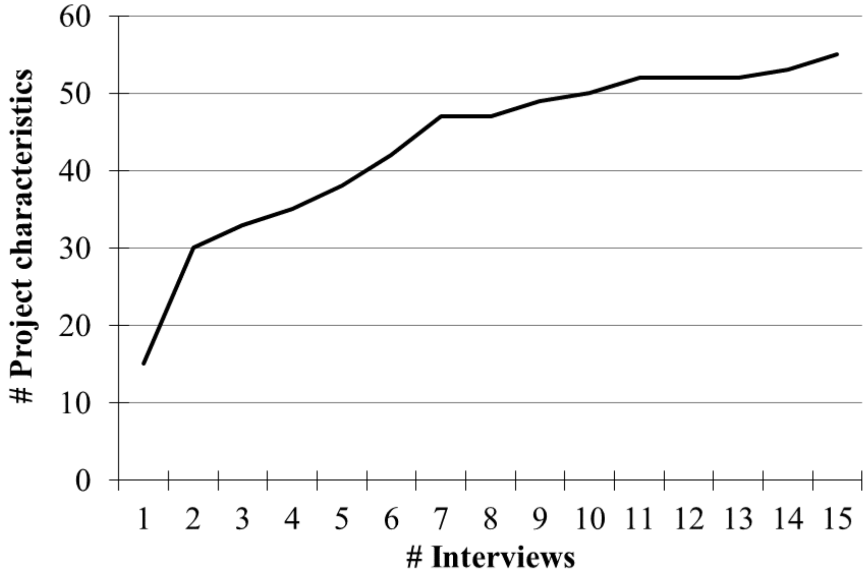


Figure 4.1: Number of new project characteristics learned in each interview.

What characteristics form preferences for wind projects? In

Table **4.3** we summarize the characteristics discussed across interview participants for the existing three turbine wind project in Gloucester as well as for a hypothetical new project within varying distances from their home. We aggregated the 55 total characteristics learned across all interviews into 15 aggregated categories that we include in

Table **4.3**. For example, the aggregated category "wildlife" includes impact to both "birds" and "bats", two separate categories that we coded of the 55 total. Section SI4-D in the SI provides a full mapping of the 55 characteristics to these 15 aggregated characteristics as well as example quotes from the interviews for how we coded each characteristic. In

Table **4.3**, we present both the number of participants who mentioned the characteristics, as well as a positive to negative ratio (i.e. “P/N ratio”) of whether the characteristics formed positive or negative attitudes towards the project. A P/N ratio of 1 indicates that the characteristic was thought to be positive by all participants, whereas a P/N ratio of 0 indicates unanimous negative views. The table also shows (in the last row) whether participants were overall supportive of the project. We find that 12 of 15 participants were supportive of both the existing wind project and a new project within 5 miles of their home. Support drops to 8 of 15 for a project within 1 mile of their home, and to only 5 for an offshore project. Also, when asked about wind energy in general at the beginning of the interview, 9 of 15 participants mentioned the Cape Wind project in a negative context.

Table 4.3: Project characteristics mentioned by participants during interviews about the existing project and a hypothetical new project within different distances from the participant's home. P/N = ratio between positive and negative statements regarding the characteristic.

Attributes	Existing Project		Hypothetical New Project 5 Miles		<1 Mile		Offshore	
	#	P/N Ratio*	#	P/N Ratio	#	P/N Ratio	#	P/N Ratio
Visual	15	0.5	6	0.6	12**	0.4	11**	0.2
Climate change / renewable	13	1	-	-	1	1	3	1
Economics	13	0.7	3	0.5	9	0.8	6**	0.3
Personal experience with wind	6	0.8	-	-	1	1	-	-
Specific Site	6	0.75	2	1	2**	0	-	-
Community identity	5	1	1**	0	1**	0	3**	0.3
Local environment	1	1	-	-	-	-	5**	0
Noise and flicker effects	11**	0.4	-	-	11**	0	-	-
Wildlife	7**	0.2	1**	0	2**	0	8**	0
Proximity	7**	0.2	5**	0.3	3**	0	-	-
Process / communication	6**	0	-	-	3**	0	-	-
Size (number of turbines)	4**	0	1**	0	2**	0	-	-
Safety / hazard	3**	0.3	1**	0	3**	0	6**	0.2
Construction	2**	-	-	-	2**	0	1**	0
Fishing	-	-	-	-	-	-	6**	0.2
# Supportive	12		12		8		5	

** 1 = always positive, 0 = always negative.*
The ratio excludes when participants expressed neutral attitudes towards the characteristic.

*** P/N ratios < 0.5*

For the existing wind project, visual appearance was the only characteristic mentioned by all participants. Participants where split on whether the visual appearance was something they liked or not, with 7 participants mentioning it positively, and 7 negatively. Participants provided very similar responses for a new project within 5 miles of their home, which is about the maximum distance that residents live from the existing project. However, visual aspect had an overall negative perception when located within a mile of someone's home (PN ratio of 0.4). Similarly, the P/N ratio was very low (0.2) for the visual aspect of a hypothetical offshore project. Only 2 of the 11 participants mentioned it positively.

Thirteen participants considered the economic aspects of the existing wind project, most of them positively (PN ratio 0.7). This is likely because of local community involvement with project economics. One of the turbines is owned by the city and is used to offset energy costs at municipal buildings, such as public schools, while the other 2 are owned by a local engineering company (Rosenberg, 2013). Similarly, for the project within 1 mile of their home, participants reiterated the economic benefits that they expect the city to receive from the project.

Community identity, local environmental impacts, and the specific site location were regarded positively for the existing project, but less often for new projects. Again, participants were overwhelmingly negative of the offshore project. Finally, only two characteristics were discussed positively across all projects: those were climate change/renewable energy benefits of the project and prior experience with energy. For example, one participant said, "my experience with [the existing project] has been positive … [the turbines] are in my backyard and it's OK."

Negative characteristics reported by the participants included noise and flicker effects (mentioned by 11 participants). Surprisingly, only 2 of the 9 participants living within 1 mile of the existing project had overall negative statements about noise and flicker effect, and 3 of the 9 had positive statements, such as how the effects are likely minimal and often exaggerated. Concerns about noise and flicker were stronger when discussing a hypothetical new project – 11 participants expressed strong concerns about the potential noise impacts if the project was sited within a mile of their home, and even those with overall support for a new project wanted to know more about potential noise impacts.

Proximity to a project was mentioned frequently, mostly in a negative context. Seven participants said that their opinion of the existing project would likely change if they lived closer to it. For example, one participant said: “if they were sitting in my backyard, I might feel differently.” Regarding a new project 5 miles away, one participant explained that they would “like [the project] better if it was along the horizon rather than right outside [their home].” Five participants made similar claims. Similarly, proximity was mentioned as a negative characteristic by 3 participants for projects within 1 mile of their home. As one participant noted, “maybe I couldn't do anything about [a project built within a mile of me], maybe I would move away.”

Process/communication was also viewed as a negative characteristic about the existing project. Six participants expressed anger at the lack of communication about the project’s construction and their surprise when it was eventually built. Safety was also a concern to some participants for all projects.

Wildlife was another major concern. For the existing project there was some concern about the impact to birds, but most saw the problem as well managed. However, wildlife impacts for future projects were unanimously negative. In addition to bird impacts, many were worried about the impact to marine life resulting from an offshore project. However, even though presented in a negative context, most concerns were raised as questions about the potential impact, not as belief statements. When discussing offshore projects, 6 participants also talked about the fishing and boating industry in Gloucester, which is a historic fishing town. There has been a recent effort by the National Oceanographic Atmospheric Association to limit the amount of fishing due to environmental concerns about depleting fish stocks. This has strained the local economy and frustrated many locals (Elias, 2013). Therefore, several participants mentioned their concern about how offshore turbines might interfere with fishing, further straining an already struggling local industry. Lastly, the number of turbines, and temporary construction from the project were regarded as negative characteristics.

Which characteristics rank most important? During the open-ended portion of the interview, the interviewer noted the various characteristics discussed by the participant throughout the conversation, and, after the questions, asked participants to rank each one in importance (Figure 4.2). The height of each bar in Figure 4.2 represents the number of participants who mentioned a particular characteristic, and the different shading shows the ranking as 1st (most important) 2nd, 3rd, or lower (less important). Figure 4.2 only shows characteristics that ranked in the top three for any participant.

The economic benefit from the project, to participants and their community, was consistently ranked highly – four participants ranked it as most important, another four ranked it as 2nd most important, and three others ranked it as 3rd. This was a common theme during interviews, for participants with both positive and negative attitudes towards wind projects. Similar to past work (Devine-Wright, 2005b; Wolsink, 2000), we find that participants were also strongly influenced by visual impact, which ranked top three most important for seven participants. Economic benefits and visual impact were often discussed together. This suggests that individuals would develop more positive attitudes about a project if economic (and other) benefits were sufficiently high; despite concerns about other factors – like in this the case, visual impact. Noise, wildlife impacts, and concerns about addressing climate change / increasing the amount of renewable energy also ranked highly among participants. For a few participants, safety of the project was also listed as one of the most important attributes, but was mentioned less frequently.

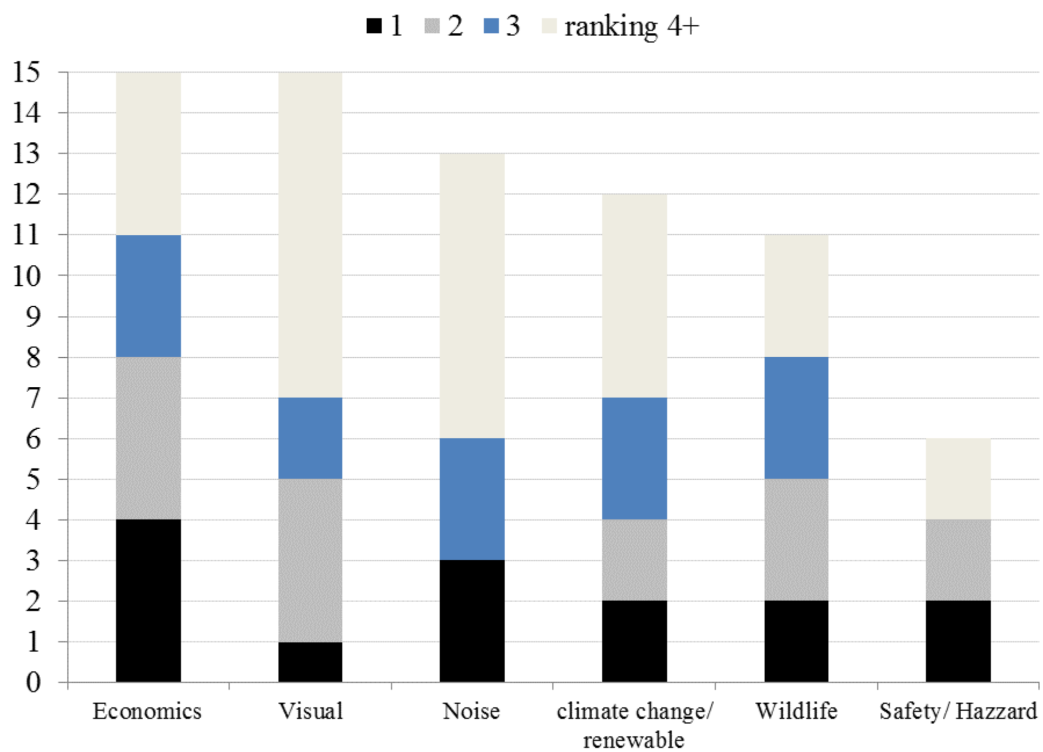


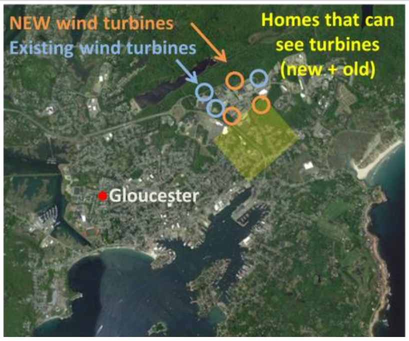
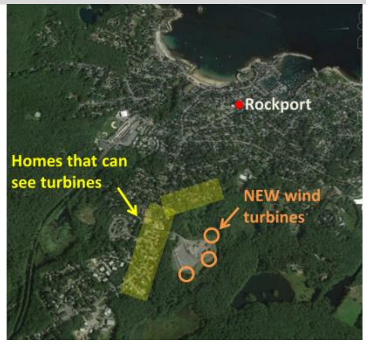
Figure 4.2: Ranking of most important project characteristics to interviewed participants.

Given a set of possible projects, which one is preferred? When presented with the prospect of a new three turbine project in their community, 8 interview participants selected to expand on the existing project in Gloucester. Six of these participants liked this option because wind turbines "are already there" and the community is "accustomed to seeing them already." We label this reasoning as 'experience with wind energy' since it implies that past experience with wind energy will limit the perceived cost relative to the other options. Two other participants chose this option because they preferred to keep economic benefits nearby in Gloucester, rather than having them go to Rockport (labeled as 'economics'). However, not all participants liked this option. One participant ranked this option last, claiming that the project would look "too cluttered," and feared that noise impacts would increase with more turbines (labeled as 'visual/noise').

Alternatively, seven participants preferred the option to build a new project in Rockport at the town dump instead. The most common justification was that the Rockport project would be "out of the way" and located "far enough away from people's houses" in their opinion, as opposed to in Gloucester, which is more populated and already has a project (labeled as 'proximity'). Another participant liked the option in Rockport because "there is a strong possibility that these could provide all electricity for Rockport, it's not a big town," suggesting that Rockport would benefit most from a new project in the area (labeled as 'economics'). One other participant liked the idea of siting the project at the dump and recycling center (known locally as the "transfer station"), which the participant found fitting for a renewable project since it's where the community "transfers energy, [and] … recycles". We labeled this as 'specific site,' which implies a preference for the specific site itself. Another participant stated for similar reasons that they didn't like the site (bottom choice), since they think it "looks so weird putting it in a dump", and said they would "rather have it in the industrial park [near Gloucester's existing wind project]". Lastly, one participant thought the project would take away from the "old charm aspect to Rockport and [would be less of an effect in] Gloucester, which is a bit more urban in the downtown area." We labeled this reasoning as 'community identity'.

Surprisingly, not one participant selected an offshore project option as their top choice. In fact, 12 of the 15 participants selected the offshore project as their bottom choice mainly due to the visual impact, which was mentioned by 11 participants. As one of these participants explains, the ocean landscape is considered "sacred" in the community and is "part of their legacy," which evoked strong negative emotions about the prospect of an offshore project (labeled as 'visual / community identity'). One participant also expressed concerns about the additional cost of an offshore project, which would therefore not yield as many financial benefits to the community as an onshore project (labeled as 'economics').

Table 4.4: Results from choice task.

	Expansion onshore	New onshore	Offshore*
			
Top Choice	8	7	0
Reason	Experience with wind energy (6) Economics (2)	Proximity to homes (5) Economics (1) Site specific (1)	
Bottom Choice	1	2	12
Reason	Visual / Noise (1)	Community Identity (1) Specific site (1)	Visual / Community Identify (11) Economics (1)

** During interviews, we included a fourth option for an offshore project in Rockport. In this figure we present results for both offshore projects combined since participants viewed the two project opinions as almost identical*

Influence diagram of the mental model for wind project preferences: Figure 4.3 illustrates the mental model influence diagram for communities regarding local wind project development. Blue ovals represent project attributes that shape general preferences about a specific wind project (orange rectangle), and dark arrows show direct links as opposed to indirect links (dashed arrows). We developed the figure based on Wolsink (2000). The diagram shows how preference for a proposed wind project is influenced by general attitudes towards wind power, annoyance factors (i.e., noise impacts), visual impacts, NIMBY preferences (which we include as ‘proximity’), desire for clean energy (which we define as ‘climate change/ renewable’), and opinions about a citizen’s ability to influence public decisions (which we include as ‘process/ communication’). As done in Wolsink (2000), we make a distinction between ‘general perception’ of wind power and perception of a specific wind project, since different factors influence these concepts.

We represent all factors identified as most important to our interview participants from our ranking exercise. This includes the additions of 'economics' (to both individuals and the surrounding community), 'safety' (whether participants think the project may be at risk of safety or hazard concerns), and 'local environment' (which includes wildlife impacts and landscape protection). We also add attributes cited frequently during our choice experiment with interview participants. These include 'experience with wind energy' and 'community identity'.

The indirect links (noted with dashed lines) show how different concepts relate to each other. Like done in Wolsink (2000), we link visual impact to both general perception of wind energy and perception of specific wind projects. We also link visual to proximity to someone's home, since they were always mentioned together during our interviews. Similarly, experience with wind energy, such as living near an existing project, affects both general attitudes about wind energy (Ek, 2005; Warren et al., 2005) and about specific wind projects (Krohn and Damborg, 1999; Swofford and Slattery, 2010) – we therefore add separate links. We also link community identity to personal experience with wind energy since it clearly changes a community's identity over time. As one of our interview participants noted, the turbines now "blend into the landscape" and "distinguish Gloucester from other towns."

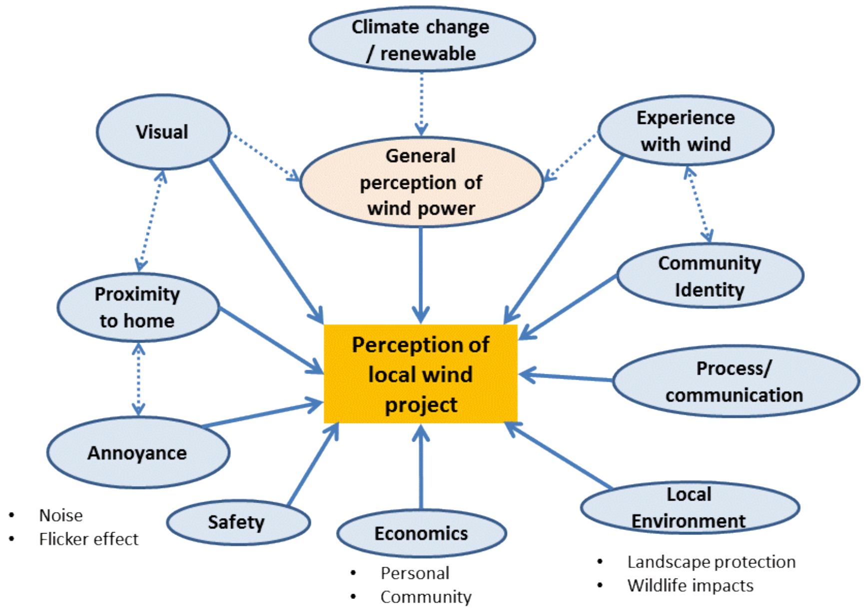


Figure 4.3: Mental model influence diagram of local wind energy projects within a community. Blue circles are project attributes that influence perceptions of a specific wind project. Solid arrows show direct links and dashed arrows show indirect links.

4.4 Discussion

We study the perceptions of wind projects from members of a coastal Massachusetts community that has an existing wind project. Through a combination of open-ended questions, a ranking exercise of project attributes, and a choice experiment, we learned the key concepts and project characteristics that help shape their attitudes towards an existing wind project as well as hypothetical new projects in their community. We identify several attributes that affect preferences for new projects, with the most important being economic benefits, visual impact, noise, climate change / renewable energy benefits, and safety concerns. Most of these attributes are addressable with responsible project development. Noise impacts and safety concerns can be managed by locating the project within a reasonable distance from homes. Efforts are currently being made in Massachusetts to identify appropriate distance through the MassDEP Wind Turbine Noise Technical Advisory Group (2016b). Climate change / renewable energy benefits are unlikely to vary by project. However, economic benefits and visual impacts do vary by project, and therefore deserve careful attention from project developers and policymakers when siting new wind projects.

Project economics for existing and future projects should be communicated more clearly. Several of our participants didn't know that the city of Gloucester benefits from the wind project through reduced energy costs. A simple solution could be to periodically include information on residential energy bills about the project's contributions to the city. This would likely improve the perception of the project, even for those who dislike how it looks. Unfortunately, there is very little standardization for how economic benefits are shared within a community – Gloucester's case is only anecdotal. For example, Newburyport Massachusetts has a single wind turbine, owned by a local woodworking company, that doesn't share economic benefits with the city, but still makes a distinguishable mark on the landscape as the only wind project in the area (Swart, 2010). Other projects not only benefit the local government, but also local residents directly. For example, the Block Island offshore wind project off the coast of Rhode Island is expected to lower household energy bills in the local community by up to 40% (2016a). Not all communities share the same set of preferences, but as we observed, economic benefit is a critical component in shaping opinions of wind energy. Therefore, if policymakers want to encourage the widespread implementation of wind projects, we recommend they develop a set of standards for how to share benefits.

The visual aspect of turbines is the most apparent characteristic of wind projects, and as we learned, strongly influences perceptions of wind energy. Therefore, project developers must be careful where they decide to build new projects. Our sample in Gloucester and Rockport showed strong negative reactions to the prospect of an offshore wind project, but seemed supportive of expanding the existing one. This example highlights the importance of learning the specific set of preferences within a community in which projects are built. Early engagement with a community about what type of project they would find most acceptable would be a great start. It only takes one controversial wind project – like Cape Wind – to negatively impact the general image of wind development (9 of our 15 participants mentioned Cape Wind in a negative context during our interviews). If the United States is to meet the Department of Energy's target of installing 224,000 MW of total installed wind capacity by 2030 (DOE, 2015), developers will have to be sensitive about how communities perceive the visual aspects of wind projects.

We also find evidence that there is a preference to avoid having a project within a certain distance of people's homes, i.e., a NIMBY effect. Seven of the 15 participants said their opinion of the existing project would change if it was closer to their home. Similarly, support for a new project dropped from 12 participants to 8 when the distance from their home changed from 5 miles to within 1 mile. However, there is also evidence that proximity isn't important to participants. Six of the 9 participants who live within 1 mile of the existing project were supportive of expanding on it with three new turbines as opposed to the other project options in the choice task. Furthermore, when discussing proximity to a project, participants often brought up other characteristics important to them. For example, when asked about a project within 1 mile from her/his home one participant said, "if we could generate as much [energy] as possible for essentially free because we're just using [the wind], I think I would be all for it." This example demonstrates that preference for distance is entangle with other factors, like in this participant's case, economics benefits to their community. It's therefore unclear how strong preferences are for NIMBY alone. Future research is needed to systematically test for NIMBY effects when controlling for other relevant factors.

Chapter 5

5 Valuing NIMBY for new wind projects in coastal Massachusetts communities using conjoint-based surveys

This work is being prepared for submission to a journal as the reference below. The chapter uses "we" instead of "I" to reflect the contributions of my co-authors.

> *Lamy, Julian, Inês Azevedo, Wändi Bruine de Bruin, and M. Granger Morgan. "Valuing NIMBY for new wind projects in coastal Massachusetts communities using conjoint-based surveys." Working Paper, August 2016.*

5.1 Introduction

In order to address climate change and to move towards sustainable, affordable, and environmentally just energy systems, a new portfolio of electricity generation technologies is required (Hoffert et al., 2002). Wind energy will likely be an important contributor to this transition in the United States, where 29 states require minimum levels of wind generation through renewable portfolio standards (DSIRE, 2015). The U.S. Department of Energy projects that total wind power capacity will reach 224,000 megawatts (MW) by 2030, tripling the current capacity already installed (DOE, 2015). However, public perceptions of wind energy projects in local communities often present challenges to development.

Massachusetts, in particular, is poised to become a leader in wind energy given its ambitious goal of building 2,000 MW of wind power by 2020 compared to today's installed capacity of 100 MW (2015; U.S. Geological Survey, 2015). The region's geography is unique since it offers the possibility of onshore and offshore projects, both of which are being pursued aggressively. State legislatures recently passed a bill that requires utilities to procure 1,600 MW of offshore wind by 2027 (Harvey, 2016). Furthermore, the first U.S. offshore wind project consisting of 5 turbines off the coast of the nearby State of Rhode Island, is expected to begin operation in the Fall of 2016 (Tweed, 2016). However, despite large general public support for it, offshore development has also provoked considerable controversy in Massachusetts. The infamous 130 turbine Cape Wind project in Nantucket Sound off Cape Cod recently failed to gain approval (McNamara, 2015). Even in 2007, during the project's early-stages, only 58% of nearby residents were supportive compared to 84% among all Massachusetts residents (Civil Society Institute, 2007). Some argued that this difference was due to not-in-my-backyard (NIMBY) sentiments – the desire of local residents to avoid having a wind project sited near their home, even though they support wind development elsewhere (McNamara, 2015). If NIMBY were true in general, it would present a public policy dilemma since a general public decision cannot be implemented if each member of the public opposes local action on that same decision.

However, the NIMBY explanation alone is incomplete since it does not clarify the underlying reasons for opposition, which are often quite complex. Firestone and Kempton (2007) surveyed over 500 residents of the Cape Cod community and find that the majority anticipated negative impacts from the Cape Wind project. This was true even among those who supported Cape Wind. The most frequently cited concern was impact to ocean wildlife and environment caused by the turbines. Other concerns included increased electricity rates, changes to the landscape, and impact to boating and fishing. In their preliminary interviews to their work in Cape Cod, Kempton et al. (2005) also found that cultural identity with ocean views was a strong factor in shaping negative opinions of the project, which was perceived as an "industrialization" of the landscape. Therefore, what might have appeared to some as a NIMBY issue was actually a combination of deeper factors that defined community attitudes towards the project.

As demonstrated in the review by Devine-Wright (2005b), many studies have challenged the sufficiency of the NIMBY explanation by arguing that other more justifiable reasons are tied to NIMBY such as characteristics that are physical (i.e., size of turbines, number of turbines, landscape), symbolic (general 'fit' of the turbine within the community – i.e., "it's progressive", or "it's too industrial"), and contextual (communication about the decision-making process, community involvement with the project, and project ownership). Most studies agree that a multi-dimensional treatment of project-specific factors is required to accurately measure attitudes towards local wind projects (Devine-Wright, 2005a, 2009, 2011; Ek, 2005; Wolsink, 2000, 2007). Furthermore, improved knowledge of the benefits, costs, and limitations of different energy technologies has been shown to improve preferences for new technology, as demonstrated in Fleishman et al. (2010) for Carbon Capture and Storage projects. However, few studies have systematically explored whether and how preferences change with distance from a wind project (i.e., what we refer to as NIMBY) in the United States (Krueger et al., 2011; Swofford and Slattery, 2010), and, to the authors' knowledge, none have done so in Massachusetts. Nor has any study attempted to estimate potential welfare loss in the State due to proximity with wind projects.

Another important dimension of preferences regarding wind project characteristics is whether coastal communities would prefer to site wind projects offshore instead of onshore. Ek and Persson (2014) find that residents across Sweden are willing to pay $0.30/kWh ($2016) more for electricity to site a 30 turbine wind project offshore as opposed to onshore. Ladenburg (2008) finds similar results in Denmark, showing that general public opinion was more positive for offshore wind development than for onshore development. However, neither study focuses on local opinions of a specific project. As with the Cape Wind project, local communities may respond differently from the general public. For example, using a choice experiment, Krueger et al. (2011) show that the perceived "visual dis-amenity cost" – the monetary cost of viewing a wind project from shore – of a hypothetical 500 turbine offshore wind project (3.6 miles from shore) in Delaware is higher for those living on the coast ($81 per year, in 2016 $) than those living inland ($11 per year). In contrast, in a sample of coastal residents in North Carolina, Landry et al. (2012) find little evidence of welfare losses and tourism impacts to beaches for a hypothetical 100 turbine wind project 4 miles from shore. Overall, it is unclear how coastal communities in the U.S. feel about the choice between onshore and offshore projects, especially how each relates to NIMBY preferences.

Conjoint-based surveys, which rely on choice experiments with hypothetical alternatives, are frequently used to estimate the monetary value of preferences, often for consumer products (Helveston et al., 2015; Min et al., 2014; Train, 2009). This method is convenient since it can be customized to answer specific research questions about the sample population. Cropper et al. (1993) shows that discrete choice experiments yield similar results to hedonic methods that rely on historical prices to estimate the value of product attributes. Similarly, Hainmueller et al. (2015) shows that results from conjoint-based surveys accurately match human decision-making for officials deciding on immigration applications. Several studies have used conjoint-based surveys to estimate utility functions for wind projects with varying characteristics, such as wildlife preservation efforts, visual changes to the landscape, ownership, and community involvement (Álvarez-Farizo and Hanley, 2002; Dimitropoulos and Kontoleon, 2009; Ek and Persson, 2014), and more generally for choices of energy related technologies and strategies (Helveston et al., 2015; Min et al., 2014). These studies also often include a price or savings component associated with the project such as a renewable energy fee to residents in the community (i.e., a cost for the project), or a subsidy (i.e., increased savings from the project). Utility functions are then used to estimate the willingness-to-pay (WTP if there is a cost) or willingness-to-accept (WTA if there is economic savings) of the various project characteristics. The result is a monetary value of each characteristic tested.

No study to date has used discrete choice methods to estimate the WTP or WTA for the distance between a person's home and a new wind project – which provides a quantification of NIMBY effects. Knowing this value should help policymakers make tradeoffs between siting projects close to communities rather than in more remote locations, where it's often more costly to site projects (see Chapters 2 and 3). It could also help wind project developers identify how much economic benefit they should offer communities where they plan to propose new projects. If benefits outweigh the perceived NIMBY value, then communities will likely be more accepting of new projects. Similarly, few studies have measured the implied value of preferences for onshore compared to offshore projects (Ek and Persson, 2014), and none have focused on the United States. The closest related work is from authors who use surveys to measure general attitudes of wind power for participants at varying distances from existing wind projects, but don't explicitly measure WTP or WTA to increase distance from a newly proposed wind project (Ek, 2005; Swofford and Slattery, 2010; Van der Horst, 2007; Warren et al., 2005). Several studies evaluated WTP or WTA for increased distance of offshore wind projects from shore (Krueger et al., 2011; Ladenburg and Dubgaard, 2009; Landry et al., 2012). However, distance in these studies is strictly used to measure the impact on ocean views (the farther away, the harder to see from shore), not the perceived disutility of proximity to someone's home.

Other studies have used econometric methods to measure the reduction in home values due to proximity with wind projects. For example, Gibbons (2013) finds that home prices in the United Kingdom dropped by 5-6% within 2 km of an existing wind project, 2% between 2 to 4 km, and 1% within 14 km. Similarly, Heintzelman and Tuttle (2012) find that wind turbines did indeed impact home values in two counties in New York. On the other hand, Hoen et al. (2014) find no conclusive evidence of property value impacts from wind turbines across the United States. As suggested by Hoen et al. (2014), these results may differ because a large amount of data is required to accurately measure the proximity effect. Heintzelman and Tuttle (2012) used 35 observations of homes within one mile of wind projects whereas Hoen et al. (2014) used close to 1,200. There may also be a regional component to this effect, which was not tested in either study. Furthermore, these papers only measure the impact as a function of distance from a wind project, and don't systematically account for the various project characteristics that shape public opinions of them.

In this chapter, we present results from a conjoint-based choice survey that we use to estimate WTA for wind project characteristics, including preferences for increased distance from someone's home and whether the project is onshore or offshore. We sample from the city of Gloucester and town of Rockport, which are 5 miles apart, north of Boston on the Massachusetts coast. Our study focuses on one community (Gloucester and Rockport collectively) in order to present realistic and specific project options to participants knowledgeable of the locations, rather than a generic set of projects. We chose the Gloucester and Rockport community because it has similar demographics to other coastal Massachusetts towns (see SI4-A in Supporting Information – i.e., SI), and already has three onshore wind turbines in Gloucester constructed in 2012. Therefore, with this community, we can also test if residents prefer expanding on the existing project compared to building a new project at a different site – another attribute we include in our choice experiment. Our aim was to present participants with a typical project that coastal communities across Massachusetts could face in the near future. We therefore focus on a 3 turbine project, the average size of existing onshore projects in Massachusetts (U.S. Geological Survey, 2015), the same size as the existing project in Gloucester, and similar in size to the first offshore wind project in the U.S. (5 turbines, Tweed (2016)).

We designed the choice survey based on information learned from preliminary semi-structured face-to-face interviews we conducted with a sample population in Gloucester and Rockport (see Chapter 4). The interviews, informed by the mental models approach developed by Morgan *et al.* (2001), revealed that economic benefits to the community and to individuals strongly influenced opinions of future projects in their community. Many interview participants also had strong negative opinions of offshore wind projects, similar to residents near the Cape Wind project (Kempton et al., 2005). We therefore included information about these characteristics for different project options in our choice experiment. Many interview participants were also concerned about noise from the project, as well as impacts on birds. Although we didn't measure these characteristics directly, in the background portion of the survey, we provided a justification for why these impacts would be minimized for all projects we presented (see Section 5.4 for more detail, and Section SI5-C for the full survey).

In the final survey, participants were told that a new wind project would be built somewhere in Massachusetts. Several alternative projects with different attributes were presented, and participants were asked to choose which one they prefer. Specifically, each participant was asked to complete 5 choice tasks in screens showing 3 potential alternatives per task. The design of the choice experiment was such that the levels of the attributes were balanced and orthogonal. Figure 5.1 shows one example of a choice task. The attributes included for each alternative were (i) the location of the project, (ii) the anticipated savings on monthly energy bill ($0, $5, $10, or $20 per month), and (iii) the increased tax revenue to the local community ($0, $250,000, or $500,000 per year). The map shows the project as an expansion of an existing onshore project, a new onshore project, or an offshore project. It also shows whether the project is to be located in the Gloucester/Rockport community or in a community 80 miles south, in Kingston/ Plymouth, Massachusetts. Using results from this survey, we estimate utility functions of project preferences using a mixed-logit regression (see Section 5.4 for more information), and estimate WTA for different project attributes. In the Supporting Information (SI), Section SI5-C, we reproduce an example of the full survey.

We also present a comparison of the Gloucester and Rockport sample with a U.S.-wide sample, in which online survey participants were asked to *imagine* they lived within a coastal community with the same attributes as Gloucester and Rockport, and were presented with the same choice experiment (including the same maps, with updated labels to be generic – i.e., "your town" instead of "Gloucester", see Section SI5-D of the SI for a version of the full survey). Using these two samples, we can compare how preferences differ between the residents of a Massachusetts coastal community likely to face the prospect of a new wind project, and the general U.S. population who may not.

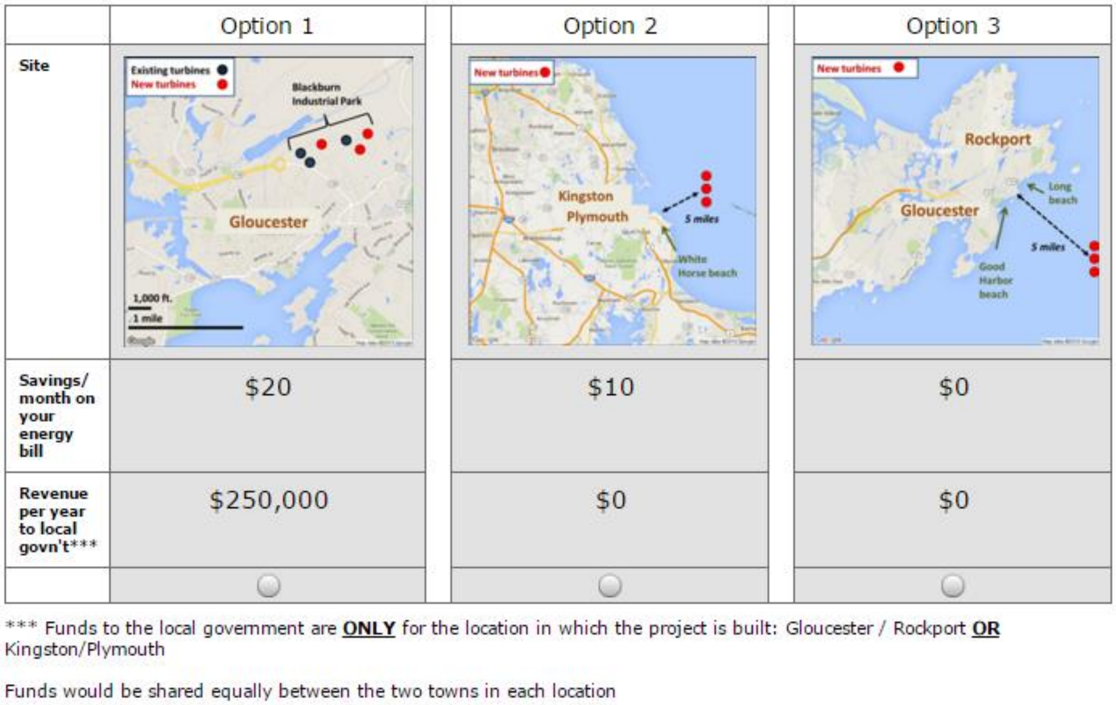


Figure 5.1: Example of one of the choice tasks in the survey distributed to the Gloucester/Rockport sample.

5.2 Results and Analysis

Our sample includes 192 participants from the coastal Massachusetts communities of Gloucester and Rockport. These respondents were recruited in-person – who took the survey on a tablet – and through an online advertisement at a local newspaper – in which case they took the survey online. We also recruited 318 participants from the U.S.-wide population recruited online through Amazon's Mechanical Turk. Each participant was paid with a $5 Amazon gift card. In Section 5.4 we provide more information about our survey and in Section SI5-A of the SI we provide more details about our samples.

Here we present our main findings as well as the willingness-to-accept values for different wind project characteristics. For different project characteristics, Figure 5.2 shows a 90% confidence interval of the WTA estimates that represent the heterogeneity of preferences across our samples. Also included in the figure is the mean WTA (circles), with error bars showing model uncertainty in parameter estimates. All model coefficients and corresponding statistics from the mixed-logit regressions are available in Section

SI5-B of the SI, and a description of our model and estimation methods is presented in Section 5.4. We organize our findings as follows: First, for the two samples we assess the effect of economic variables, preference for distance from a project (i.e., NIMBY effect), preference for onshore or offshore, and preference for building the project at an existing site instead of a new one. We then offer possible reasons why differences exist between the samples.

Are economic benefits important? Personal savings on electricity bills and tax revenue to the community were the strongest predictors of whether or not a participant would choose a project. However, the magnitude of this effect was different between the two samples. Savings were 4 times more important (larger coefficient value in our estimated statistical model) in the U.S.-wide sample than in the Massachusetts coastal community, and tax revenue was 50% more important for the U.S.-wide sample (see Section SI5-B of the SI). Both samples regard tax revenue to the community as the most important project characteristic over all others. This preference is stronger when the project is located within their community (tested using an interaction term), which ensures that the increased tax revenue would go to their local government. These results are consistent with those of Devine-Wright (2005a) and Ek (2005), who argued that economic involvement from the community improves public support, and with Guo et al. (2015) who shows that economic benefits and environmental costs are the most important factors in predicting wind project acceptance for communities in China.

Is there a NIMBY effect? We find little evidence of preferences for distance from a project for participants in the Massachusetts coastal community. Across all subgroups we find no preference to avoid living within 1 mile of a project. Furthermore, only two small subgroups prefer to locate the wind project 80 miles away. First, participants who held negative beliefs about wind development in general perceive increased value of $36/month on average for projects 80 miles away. This effect is consistent with Wolsink (2000) and Krohn and Damborg (1999) who show that general beliefs about wind power (in this case negative) strongly affect opinions about local projects. In both samples, we also find a similar yet much smaller effect for those who agree that their community should help address climate change. Those who agree are more accepting of projects within their community. The second subgroup consists of new residents of Gloucester and Rockport (less than 10 years) who perceive an increased value of $10/month for projects 80 miles away. Based on conversations with in-person survey participants we hypothesize that these new residents likely moved to the community for vacation and/or retirement. Residents of coastal communities typically have stronger aversion to wind projects when they are thought to interfere with recreational activities, as shown by Ladenburg and Dubgaard (2009). In short, only a limited number of participants prefer locating the project in a different town entirely. Most participants in Gloucester and Rockport are comfortable locating a new wind project in their community, even within 1 mile of their home.

Participants from the broader US population, on the other hand, perceive an increased value of $1/month for wind projects greater than 1 mile from their homes (Figure 5.2). However, this effect is not present for participants who identified as having liberal politics, which is often characterized as supportive of renewable energy development. Furthermore, this implied cost is quite low. For example, if developers were to compensate individuals for the disutility of living within 1 mile of the project, it would add $60,000 per year to project costs (assuming 5,000 homes affected), only a 4% cost increase for a typical onshore project[6]. As a point of comparison, Gibbons shows historically in the United Kingdom that the negative impact to home values within 2 km (1.6 miles) of wind projects amounts to about $85/month (in 2016$). Even the 90th percentile of our WTA estimates ($38/month, Figure 5.2) is less than half this value. Gibbons however relies on revealed-value utility estimation, as opposed to our discrete-choice approach, which has been shown to yield different results (Cropper et al., 1993; Palmquist and Israngkura, 1999). Finally, we also find that, across all subgroups, participants from the broader U.S. sample have no preference for locating the wind project in another town, 80 miles away.

[6] Assumes 9 MW at $1.50/Watt, consistent with (DOE, 2015), annualized over 20 years at 8% discount rate.

Is there a preference for onshore vs. offshore? In contrast to the situation in much of Europe, participants in both samples prefer onshore to offshore projects. The coastal community in Massachusetts has a higher WTA ($13/month on average) than the U.S.-wide sample ($0.5/month on average). In other words, for Gloucester and Rockport residents, ensuring the project is onshore (and not offshore) is equivalent to increasing their monthly saving by $13 on average, compared to only $0.5 for the broader U.S. sample. This difference exists across the distribution of preferences for both samples, as shown by the 90% confidence intervals in Figure 5.2. There is also some evidence of NIMBY with preference for offshore projects. Participants in the U.S.-wide sample have a slightly higher preference for onshore if the project is located within their community (measured with an interaction term, see Section SI5-B of the SI). This effect is not present for participants in the coastal community who are equally opposed to offshore in their community and elsewhere. Lastly, we also find a slightly lower preference for onshore with residents in Rockport than in Gloucester.

Our results agree with those from Krueger et al. (2011), who estimate the perceived visual dis-amenity cost of an offshore project in Delaware at varying distances from shore using discrete choice surveys. They find that WTP to move the offshore project farther from shore is higher for residents in coastal rather than inland towns. If true, then we observe that the U.S.-wide participants in our study, who were asked to imagine they lived in a coastal community, are unable to express the same values that actual coastal communities share regarding offshore wind. Instead, their preferences, in this hypothetical exercise, are more consistent with those of residents living far from coastal areas. We also find a slightly higher preference for offshore with Gloucester and Rockport residents who are age 40 or lower. This age effect is consistent with past literature that shows a greater acceptance of offshore projects by younger generations (Krueger et al., 2011; Ladenburg, 2008; Ladenburg and Dubgaard, 2009).

From these results, we conclude that understanding local preferences is critical for the success of the projects. Suppose local policymakers were deciding whether to build an offshore project in Gloucester based on overall benefits and costs to the community, including perceived “disutility” of the project. We estimate that total welfare losses would be $5.6 million (by applying our WTA estimate of $13/month for onshore projects across 36,000 households in Gloucester and Rockport (U.S. Census Bureau, 2016)). Accounting for these losses, in addition to typical project costs, would increase annual costs by 130%[7]. However, if the project was planned based on the perceptions of the general public in the U.S. (from our U.S.-wide sample), then policymakers would have expected welfare loss of only $0.2 million, or a 5% increase in annual costs, which may be low enough to justify the project. Generally, public policies that incentivize offshore wind development based on preferences of the general public, while not fully considering the preferences of affected communities, raise concerns about procedural justice (Gale et al., 2009). For example, Massachusetts legislatures recently passed a bill that requires utilities to procure 1,600 MW of offshore wind within the next 10 years (Harvey, 2016). It remains to be seen whether this decision reflects the preferences of coastal communities, as well as of other residents in the state. Our results suggest that preferences may indeed vary between these communities.[8]

Is there a preference for building the project at an existing site? In addition to preferring onshore projects, the Massachusetts coastal community participants gain additional value if the project is sited at an existing site as opposed to a new one, equivalent to an increase in electricity bills of $4/month. For the U.S.-wide sample, we don't find a significant preference for building the project at a new site or an existing site.

Difference between samples*:* Results differ between the coastal Massachusetts and U.S.-wide samples, likely for two reasons:

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[7] We assume a 9 MW project that costs $4/Watt in capital cost (consistent with Lazard (2014b)), annualized over 20 years with an 8% discount rate.

[8] Although we do not sample specifically from non-coastal communities in Massachusetts, we tested a subgroup from our MTurk sample in Massachusetts (7 of 318 total) as well as a subgroup in New England states (14 of 318 total) and found no deviation in preferences between these subgroups and the larger MTurk sample.

(1) *Prior experience with wind projects*. Most participants from our early interviews in Gloucester and Rockport reported very positive perceptions about the existing wind project in Gloucester, and thus are less likely to express a preference for increased distance away from a new project that's similar. This likely also influenced their preference for familiar onshore projects instead of offshore ones, which carry more uncertainty. On the contrary, only 9 of the 318 participants in our U.S.-wide sample live within 20 miles of an existing wind project[9], and thus participants from this sample have less familiarity with wind projects. This difference may also explain why increased economic benefits (savings and tax revenue) are more important to the broader U.S. sample. Because they have less knowledge and experience to draw upon in making their choice among projects, participants from the broader U.S. sample are motivated by more familiar economic variables. This likely also explains the slightly lower preference for onshore projects with Rockport residents, since they have less direct experience with the existing wind project than Gloucester residents. Ladenburg (2008) and Van der Horst (2007) show that past experience and knowledge gained from living near existing projects affects beliefs about new ones. Similarly, Warren et al. (2005) show that residents in Ireland and Scotland living near existing onshore wind projects were more supportive of wind power in general than the broader population.

(2) *Cultural Identity*: Another noteworthy difference between the samples is that, in our preliminary interviews, Gloucester and Rockport residents reported a strong cultural identity with ocean landscapes. One preliminary interview participant called the ocean landscape "the town's legacy", and explained that they "wouldn't want to have it spoiled by [an offshore project]". Twelve of the fifteen people interviewed reported that they disapproved of offshore wind development for similar reasons (see Chapter 4). Similar results were found for Cape Cod residents in their reaction to the Cape Wind project Kempton et al. (2005). This result is also consistent with Devine-Wright (2009), who shows that place attachment

[9] This was computed by comparing zip codes of survey participants to a dataset of existing wind projects from the U.S. Geological Survey (U.S. Geological Survey, 2015)

significantly drives preferences for wind projects, and argues for the abandonment of a more simplistic NIMBY theory.

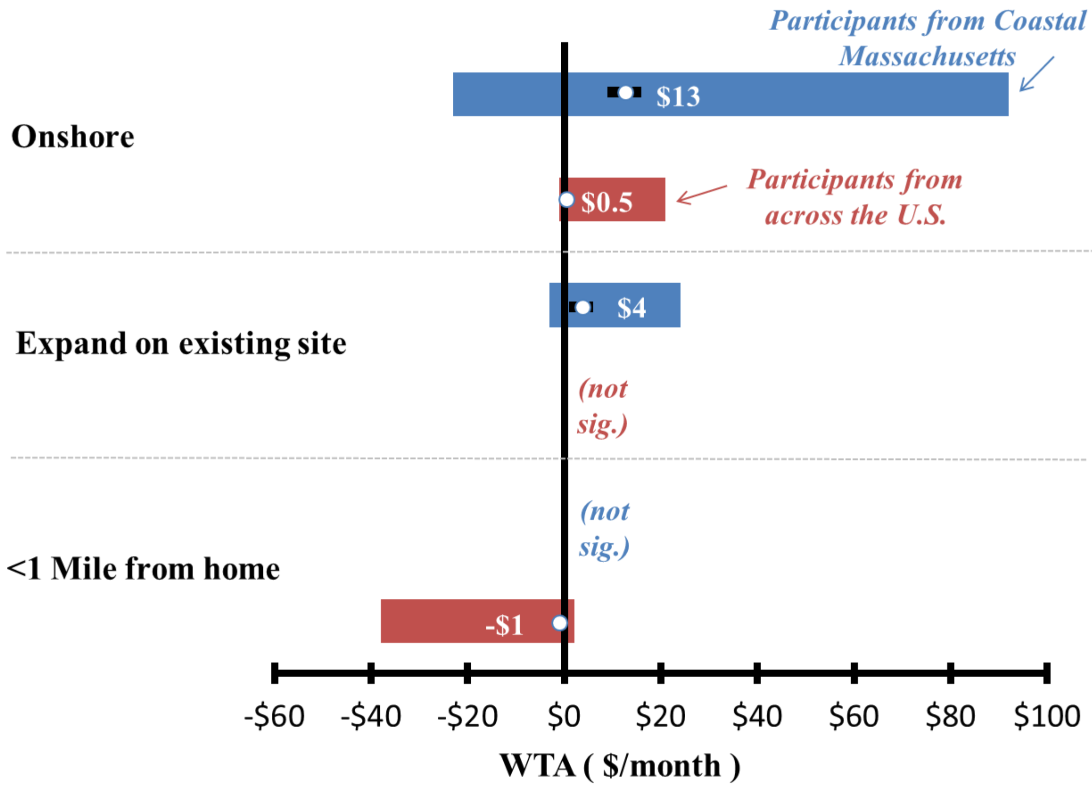


Figure 5.2*:* Willingness -to-accept (WTA) estimates in $/month (horizontal axis) for different wind project characteristics for the two samples. Positive values show an increase in overall utility. The colored bars show the heterogeneity of preferences (90% confidence intervals) across our sample population. The circles represent mean WTA with error bars showing uncertainty (90% confidence interval) in the mean estimates from our model. Estimates are only for variables that were significant at 10% in Model2 presented in Table S5 and Table S6 in the SI. For example, "<1 Mile from home" was not significant for the Massachusetts Coastal sample, so is excluded from this figure.

5.3 Discussion

We hypothesized that NIMBY preferences might exist for wind projects in coastal communities in Massachusetts, a state that has experienced significant challenges with wind development – exemplified by the Cape Wind project. On the contrary we find little evidence of NIMBY in the towns of Gloucester and Rockport, but a small effect for the broader U.S. sample. This difference is likely because of the positive experience that Gloucester and Rockport residents have with an existing wind project, compared to the limited experience with wind energy from the U.S. sample. In both samples, economic benefits were the strongest predictors of selecting a project. We also find that many Gloucester and Rockport residents prefer expanding on the existing project in Gloucester, rather than building one at an entirely new site. This preference is equivalent to $1.7 million per year across residents.

Local community involvement with the project is well documented in the literature as an important driver of public support (Devine-Wright, 2005a; Ek and Persson, 2014; Krohn and Damborg, 1999). This is likely the case in Gloucester. For example, one turbine in is owned by the city of Gloucester and helps reduce energy costs to municipal buildings, including public schools. The other two turbines are owned by a local engineering company, which has been in the community for over 50 years. Developers also held town hall meetings about the project prior to its construction, and even had a blade-signing ceremony when the turbines were erected (Rosenberg, 2013). However, Gloucester's example is only anecdotal. Even if there is large overall support for projects, and lack of NIMBY preferences, public resistance to projects may still arise from those who strongly opposed the project. A study across the U.S., and particularly in Massachusetts, is needed to systematic identify why historically some projects were viewed positively while others were not, and whether these views were reflective of the overall community. This would help policymakers create positive feedback loops for future projects, which would greatly help meet renewable targets.

While we use the distance from a wind project as a proxy for NIMBY, Devine-Wright (2005a) and Wolsink (2000) explain that other factors are often embedded within NIMBY. For the U.S.-wide sample, instead of NIMBY, we may be measuring the uncertainty of factors related to living within 1 mile of a project – like how it looks or whether nearby residents can hear it from their home. Even though we controlled for these factors in our experiment (see Section 5.4), there may still be an element of uncertainty – especially for those who don't regularly interact with wind turbines. Experience may help clear up these uncertainties, and doesn't necessarily have to come from living near an existing project. Improved knowledge of wind energy could come from news outlets, social media, or even popular culture (television, movies, literature, art, etc.). Slater (2007) shows that media can strongly influence and even create positive feedback loops that shape societal and cultural identity. More research is required to verify if this form of knowledge transfer can yield similar results in shaping preferences than personal experience with wind projects. If so, then policymakers and project developers should consider using these channels to improve the image of existing and future projects with the broader U.S. population.

We also find that our sample of coastal communities in Massachusetts strongly prefers to avoid offshore projects. Onshore projects were perceived to yield an increased value of $13 per month over offshore ones, equivalent to $5.6 million per year for only three turbines. This presents a fundamental problem when meeting ambitious renewable targets in Massachusetts, equivalent to 1,600 MW of new offshore capacity in 10 years (Harvey, 2016). Even if there was an option to build this capacity onshore, it would require over 500 turbines, or 178 onshore projects like the one in Gloucester (assuming a 3 MW onshore turbine (GE, 2016)). Offshore projects are much more practical since over 100 turbines could be built per project, such as the 175 turbine (630 MW) London Array project in the United Kingdom (London Array, 2016). In our experiment, we presented an offshore project 5 miles from shore, but others have shown that perceived welfare loss from offshore projects decreases with distance from shore (Krueger et al., 2011). Similarly, Ladenburg has argued for almost a decade that offshore projects in Denmark should be placed farther from shore to reduce the welfare loss to coastal communities (Ladenburg, 2008, 2014; Ladenburg and Dubgaard, 2007). A solution could be floating offshore wind turbines, which offer the possibility to locate projects over 30 miles from shore where they are not visible (Weinzettel et al., 2009). Our welfare loss estimates suggest that the additional cost of floating offshore (about 20%) may indeed be justifiable in Massachusetts (Myhr et al., 2014).

5.4 Methods and Data

Discrete Choice Survey

Participants from our coastal Massachusetts sample (Gloucester and Rockport) were told that a three turbine wind project would be built somewhere in Massachusetts, and that four characteristics would vary depending on the project, as shown in Table 5.1.

Table 5.1: Wind project attributes included in survey.

Attributes	Levels from the attributes
Community	• Gloucester / Rockport • Kingston /Plymouth (similar coastal community 80 miles South)
Project site	• Expand on an existing wind project at an industrial site • Build a new project at the town dump • Build an offshore project 5 miles from shore
Savings per month on electricity bill	• $0, $5, $10, or $20 *Based on a 2% to 9% decrease in wholesale electricity market prices associated with increased wind capacity from* Woo et al. (2011) *and assumed energy bills ranging from $75 to $203 per month in Massachusetts* (Electricity Local, 2016)
Tax Revenue to local government	• $0, $250,000, and $500,000 *Based on the tax revenue raised by the city of Gloucester from the existing three turbine wind project (~$250,000) compared to the promised revenue from the project (~$500,000) when it was proposed* (Lamont, 2015)

The "Community" attribute identifies the community in which the project is built. We chose Kingston/ Plymouth as an alternative to Gloucester / Rockport since it is also on the coast, has similar demographics, and has an existing wind project (four turbines) built in 2012 (same year as the three turbines in Gloucester). This attribute measures whether participants prefer a project in a faraway community. The "Project site" attribute serves three purposes: (1) it gives information about whether participants prefer an existing site over a new site; (2) it allows us to see if residents prefer onshore or offshore sites; and (3) it provides information about distance between the participant's home and the project, since we also collect the participant's address. We can therefore estimate the effect of living within 1 mile from the project. In the choice task, the "Community" and "Project Site" attributes were presented as one of 6 maps, summarized in Figure 5.3. We also presented economic benefits to both participants themselves (savings per month) and to their community through increased tax revenue, which we explained would be used for programs that the participant supports (education, public works, etc.). In total, there were 5 randomized choice tasks with 3 alternatives per task (an example choice task is provided in Figure 5.1). To build the survey, we used SawTooth software with the "Balanced Overlap" CBC feature, which creates a balanced and orthogonal set of choice tasks across the sample collected. The final survey was available to participants via a web address.

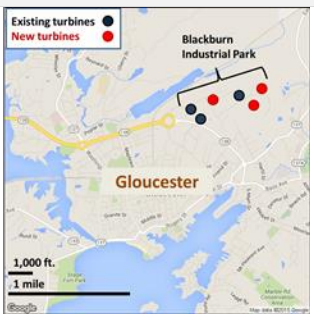
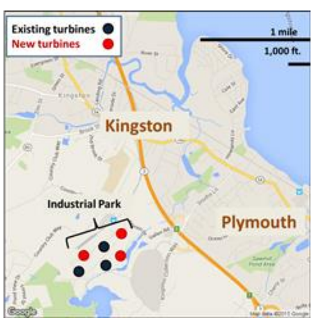
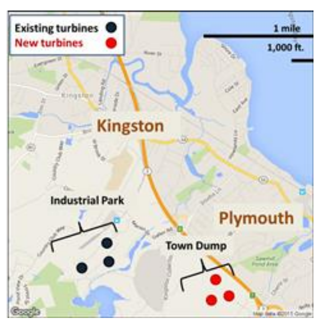
	Existing project site (industrial park)	**New Project site (town dump)**	**5 miles Offshore from local beach**
Within Local Community			
Community 80 Miles Away			

Figure 5.3: Maps shown in choice tasks presented to the Gloucester and Rockport sample.

In our preliminary interviews (see Chapter 4), we also found that noise, flicker effect, and wildlife impact were important to participants. However, these were not included in the survey since they don't typically vary by wind project within a community. In the initial introduction screens to the survey (see Section SI5-C of the SI for a full copy of the survey), we explained that these attributes would be minimized for the new project by using advanced turbine technology. As an attention check, we asked the Gloucester and Rockport participants if they indeed ignored these factors when choosing projects and over 70% reported they did. At the end of the survey, participants were asked to complete demographic information and answer questions about their beliefs on climate change and wind energy development in general.

The survey for the U.S.-wide sample (distributed via Amazon Mechanical Turk) maintained the same attributes, levels, and design as the survey for the coastal Massachusetts community, except that: (1) we asked participants to assume they hypothetically lived in a coastal town; and (2) instead of the labels "Gloucester/ Rockport" and "Kingston/ Plymouth", we used "Your Town" and "Far Away Town", respectively. Each map also specified the hypothetical location of the participant's home using a yellow icon, which was randomly placed in either Gloucester or Rockport at various locations. All other aspects of the survey were the same. The full survey for both samples is available in the SI, Sections SI5-C and SI5-D, and details about our survey samples are provided in Section SI5-A.

Utility functions

We estimate the utility function of wind project preferences using the following models (1) a multinomial regression, (2) mixed-logit estimator regression (MLE), and (3) and MLE model with participant-specific interaction terms. In MLE, specified coefficients are assumed to be random variables instead of as fixed values, representing the distribution (or heterogeneity) of coefficient values across the sample population. This result allows for more careful treatment of uncertainty in parameter estimation, and thus on our willingness-to-accept (WTA) calculations as well. Equation (1) shows how we model the utility ($U_{i,j}$) of participant (i) for wind project (j) using this approach:

(1) $$U_{i,j} = ln\left(\frac{prob_{i,j}}{1+prob_{i,j}}\right) = \sum_{k=1}^{\substack{\#\,project\\ attributes}} \left(\beta_k * ProjectAttr_{(j,k)} + \sum_{y=1}^{\substack{\#individual\\ attributes}} \beta_{k,y} * PartAttr_{(i,y)} * ProjectAttr_{(j,k)}\right) + \varepsilon_{i,j}$$

The term $prob_{i,j}$ represents the probability of participant "i" selecting project alternative "j". β_k are preference coefficients for project-specific attribute "k", $\beta_{k,y}$ are interaction coefficients for project attribute "k" and participant attribute "y", and $\varepsilon_{i,j}$ is a standard normal error term. We formulated Equation (1) using the mixed logit modeling methods described by Train (2009), with further guidance from the model developed in Min et al. (2014).

Table **5.2** shows the full list of variables that we consider in our model.

Table 5.2: Variables included in utility function estimation.

	Variable	Description	Values	Distribution for Mixed-Logit
Project-specific	$X^{SAVINGS}$	Monthly savings on energy bill	$0, $5, $10, $20 (continuous)	Log-Normal
	X^{TAXREV}	Taxes raised to the local government	$0 (base), $250000, $500000	Log-Normal
	$X^{HOMETOWN}$	Project is in subject's local community	1=yes, 0=no	Normal
	$X^{HOMETOWN\_1MILE}$	Project is <1 mile of subject's home	1=yes, 0=no	Normal
	$X^{ONSHORE}$	Project is onshore (NOT offshore)	1=yes, 0=no	Normal
	$X^{ONSHORE\_EXISTING}$	Project is at an existing wind project site	1=yes, 0=no	Normal
Individual-specific	X^{AGE}	<40 years old	1=yes, 0=no	Fixed
	$X^{SUPPORT\_WIND}$	Generally support wind development	1=yes, 0=no	Fixed
	$X^{SUPPORT\_CC}$	Agree that their community should help address climate change	1=yes, 0 =no	Fixed
	$X^{LIBERAL}$	Identify with liberal politics	1=yes, 0 =no	Fixed
	X^{HIGH_INC}	$100k + in household income	1=yes, 0 =no	Fixed
	$X^{HIGH\_HOMEVAL}$	Home value greater than $400k	1=yes, 0 =no	Fixed
Interactions for	$X^{NEW\_TO\_GR}$	Moved to Gloucester/Rockport within the last 10 years	1=yes, 0 =no	Fixed
Massachusetts community only	$X^{ROCKPORT}$	Live within Rockport (not Gloucester)	1=yes, 0 =no	Fixed

Model 2 and 3 assume preferences for "Savings" and "Tax Revenue" follow lognormal distributions since a rational individual would always prefer more personal savings and tax revenue to their local government (all else equal), thus the coefficients for these variables should always be positive. We assume all other variables follow normal distributions since it's unclear whether their effect is positive or negative across individual preferences. We also assume fixed coefficients for all interaction terms for convenience and ease of interpretation. Lastly, we treat "Savings" as a continuous variable, but keep all other variables discrete since we don't expect them to follow a continuous trend. Equation (2) shows the full model specification of our base case mixed-logit model (Model 2) for participant "i" and project choice "j". Assumed distributions are noted with superscripts; LogN(.) for lognormal, N(.) for normal, and no superscript for fixed coefficients. The tables with the full results for Models 1 to 3 are presented in the SI, Section SI5-B.

$$U_{i,j} = \beta_1^{LogN(\mu_1,\beta_1)} * X_j^{SAVINGS} + \beta_2^{LogN(\mu_2,\beta_2)} * X_j^{TAXREV} + \beta_3^{N(\mu_3,\beta_3)} * X_j^{HOME} + \beta_4^{N(\mu_4,\beta_4)} * X_j^{HOME\_1MILE} + \beta_5^{N(\mu_5,\beta_5)} * X_j^{ONSHORE} + \beta_6^{N(\mu_6,\beta_6)} * X_j^{ONSHORE\_EXISTING} + \beta_7 * \left(X_j^{TAXREV}\right) * \left(X_j^{HOME}\right) + \varepsilon_{i,j} \quad (2)$$

Willingness-to-accept (WTA) estimation

We estimate WTA by computing the ratio between the coefficients of interest and our variable "Savings". For example, by dividing β_5 by β_1 in Equation (2), we can observe how much more savings per month a participant would have to receive to have the same utility as ensuring that the project is onshore. A positive WTA represents the implied increase in monthly savings from a project attribute, or perceived increase in wealth. Using the mixed-logit regressions from Table S5 and Table S6 in SI, we represent the uncertainty in WTA estimates by running Monte Carlo simulations (10,000) of the random coefficients, assuming that the two coefficients are independent. This allows us to provide a distribution of WTA estimates for each project attribute that represents the heterogeneity of preferences across our sample, including 90% confidence intervals, instead of simply reporting an average WTA point-estimate. Results from these simulations are presented in Figure 5.2.

There are a few limitations of this approach. First, we assume that the two variable coefficients that make up the WTA ratio are independent. Fiebig et al. (2009) showed that MLE models may not accurately account for the heterogeneity across preferences due to correlation between variables. In our sample, we assume that the preference to increase “savings” per month is independent from the preference of other variables we measure, such as the desire to have a project onshore. Second, the accuracy of our estimated WTA distributions depends on the accuracy of our model in estimating the mean and standard deviation of the random variables we include. The colored bars in Figure 5.2 of Section 5.2 represent our “best guess” of these distributions (i.e., best guess for the mean and variance estimates). To account for this uncertainty, in the same figure, we also provide error bars around the mean estimate of WTA. This was done by running 10,000 Monte Carlo simulations of the mean (using the normal distribution that defines our model’s sample error) for the two random variables that make up each WTA ratio. We find that the uncertainty in the mean estimates is quite low. For example, the mean WTA for onshore in the GR sample ranges from $9 to $16/ month when accounting for model uncertainty, compared to $13 on average. We therefore argue that the distributions in Figure 5.2 are a reasonable approximation of the heterogeneity in preferences across our sample. Lastly, past literature typically uses prices to monetize preferences for different characteristics, not savings, and presents them as Willingness-To-Pay (WTP) (Helveston et al., 2015; Ladenburg and Dubgaard, 2007; Min et al., 2014; Train, 2009). Furthermore, WTA and WTP are not always equal. Hanemann (1991) argues that WTP and WTA diverge when there is limited substitutability between goods, and that WTA may diverge to infinity whereas WTP is limited by someone’s budget. However, in this analysis, we bound the monetary amount (savings/ month) at low levels ($0 to $20), and offer substitutability by presenting different levels for each attribute in our survey. We therefore argue that our WTA estimates are likely a reasonable approximation for WTP (payment / month).

Chapter 6

6 Conclusion and Policy Recommendations

Wind energy capacity in the United States is expected to triple in the next 15 years (DOE, 2015). This transition will undoubtedly help reduce greenhouse gas emissions, improve air quality, and create a more sustainable electricity grid (Hoffert et al., 2002). However, finding the right location of where to build wind energy projects requires careful thought and analysis. My work provides insights on where to site new wind projects when considering transmission requirements, wind resource potential, the temporal aspect of wind energy production, and public preferences. This information can help policymakers, regulators, wind project developers, and all other stakeholders as the country moves towards large-scale penetration of wind energy.

6.1 Summary of Results and Recommendations

In Chapter 2, for a case in MISO, I find that storage might have a role in replacing transmission capacity requirements when integrating remote wind resources, but capital costs need to be less than $100/kWh and transmission costs need to be greater than or equal to $600/MW-km. Current storage costs are uncertain, but roughly 3 to 10 times higher than $100/kWh for lithium-ion batteries and 5 times higher for sodium-sulfur batteries. Only optimistic cost estimates for CAES and used Li-ion batteries could meet this cost target. This is not to say energy storage won't play a large role in the future electricity grid. Other potentially promising applications of energy storage include providing ancillary services, arbitraging prices in energy markets, reducing peak generation capacity requirements, and facilitating the implementation of off-grid or micro-grid projects.

Chapter 3 takes a broader view of remote wind development in MISO. I find that lack of transmission infrastructure, or perceived high transmission costs, should not necessarily be the reason to dismiss wind projects in remote areas with high wind resources. It's important to consider the overall system net benefits of the potential siting locations, such as the temporal aspects of energy production from different wind projects and total wind resource potential. Knowing these benefits might reveal that it's worth investing in the transmission infrastructure to access them. I show that in order to meet 40 TWh of new wind generation in MISO, it is most economical (up to $1 billion per year) to build wind projects in remote windy states such as Iowa and Minnesota rather in Illinois, which is closer to load but has lower quality wind resources. I recommend that policymakers conduct similar analyses when making siting decisions to comply with renewable targets. For example, administrators of the renewable portfolio standard in Illinois, which makes up about half of the 40 TWh needed in MISO, should allow and encourage compliance with wind project development outside their state (like in Iowa and Minnesota). The methods and insights from this work could also be applied in other regions with strong wind resources in remote areas such as in China and the United Kingdom.

Finally, my last two chapters emphasize the importance of public perceptions and preferences when deciding on where to site wind projects. Chapter 4 explores the mental model of how individuals perceive a new wind project. Interviews with members of a coastal community in Massachusetts revealed that the economic benefit from a proposed wind project is one of the most important characteristics that drive public opinion of the project. In Chapter 5, I confirm this result with a conjoint-based choice survey, showing that members of the same coastal community and participants from a U.S.-wide sample are more likely to accept a new onshore wind project in their community if it increases local tax revenue ($250,000-$500,000 per year) and personal savings ($10 -$20 per month). Surprisingly, I also find that public preferences about where to locate new wind projects are not driven by a desire to avoid living near them (NIMBY), even within 1 mile. Instead, they are driven by preferences about the specific locations within a community, such as a desire to avoid offshore locations, or to expand on an existing project rather than building an entirely new one. I therefore strongly recommend that policymakers and project developers engage in open dialogue with communities early-on when siting new wind projects to learn their specific set of preferences. Ideally, developers should also present multiple location options so that the community is more likely to find an acceptable solution.

Ultimately, finding the optimal location of where to build a wind project requires multi-dimensional thought and analysis. This includes exploring different technologies, estimating transmission upgrade requirements, considering the variable nature of wind power production, and learning how people feel about projects in their community. My work provides insights on these topics to help improve wind project siting decisions. However, more research is needed to integrate these different aspects into a state-wide (i.e., Massachusetts) or nation-wide model which identifies optimal project locations. For example, willingness-to-accept estimates (like from Chapter 5) combined with information on transmission requirements and hourly power production could help identify specific locations for economical, reliable, and publically accepted wind projects. I provide a template for how to do this with the multi-attribute optimization model that I present in Chapter 3. This effort is sorely needed for successful integration of wind energy across the United States.

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Supporting Information (SI)

SI3: Chapter 3

Table S1: Description of additional model scenarios for sensitivity analysis presented in Figure 3.3.

Alternative energy value calculations	**MCE and LMP**: To calculate energy value, we test if using 2014 LMPs at different price nodes instead of 2014 MEC (marginal energy component of prices in MISO) changes the main conclusions from our analysis. Wind farms in Minnesota are assigned to prices from the "Minnesota Hub", farms in Illinois to the "Illinois Hub", farms in North and South Dakota to the "OTP.MPC" hub, and farms in Iowa to the "ALTW.ALTW" hub. These hubs are identified using MISO's LMP Map (2016c) and data for each price hub was downloaded directly from (MISO, 2015e). The resulting break-even transmission cost premium for ND-SD is $310/kW compared to $360/kW when using MEC (base case), still well below historical transmission cost differentials. However, the break-even value in MN-IA (Figure 3.3) is $100/kW compared to $250/kW when using MCE (base case). This large difference for MN-IA is mainly driven by the difference in LMP prices between Minnesota Hub (average of $31/MWh) and the Illinois Hub (average of $35/MWh), which lowers the energy value of wind farms in MN-IA, thus reducing their competitiveness compared to Illinois farms. Nonetheless, we still arrive at the same conclusions since the difference in historical transmission costs between MN-IA and Illinois are still well below $100/kW.
	Simple Dispatch: We also run another scenario in which we estimated marginal costs to MISO generations in each hour, instead of relying on MISO's marginal energy component (MEC) price data. For this analysis, we build a simple dispatch model of MISO generators based on the analysis in (Venkatesh et al., 2012). In the simplified dispatch model, we assume that in each hour, the marginal fuel source is either coal or gas, and assume that all other fuel sources are fixed based on 2014 data from MISO on the historical generation mix (MISO, 2016b). We then assume a fuel price for coal of $2.38/mmbtu based on EIA's annual energy outlook reference case in 2015 for year 2020 (EIA, 2015). We assume that gas fuel costs are $3.27/mmbtu, based on the Henry Hub futures price for December 2020 delivery (CME Group, 2016). Coal and gas units are then dispatched (lowest cost first) to meet 2014 MISO load in each hour (MISO, 2015b) using generators with heat rates and nameplate capacity from the U.S. EPA's EGRID dataset (EPA, 2014), which contains 299 coal and gas generators in MISO. This analysis results in an hourly dataset of marginal fuel costs to meet load in each hour of 2014. We then used this result, instead of MEC prices, to estimate the energy value of wind farms in our site selection model. With this approach we find that the resulting break-even transmission costs differ by about 20%, but yield the same qualitative conclusions (see Figure 3.3).

Wind model year	We rely on wind data from (EWITS, 2012), which spans 2004 through 2006. In the base case, we choose 2006 as our sample year, but also report results when using 2004 and 2005 model years in this section. We find that wind data in 2004 and 2005 is more favorable to wind farms in remote areas (MN-IA and ND-SD) compared to Illinois, and thus the break-even transmission cost premiums for MN-IA and ND-SD are higher when using these sample years compared to the base case. With the best wind year (2005) in our sample, the break-even transmission cost premium of ND-SD is $620/kW, which is close to, but below median historical cost premium. Similarly, in MN-IA the best wind year yields a break-even cost premium of $450/kW, which is well above the median historical cost premium. These results suggest that even in the most extreme sample years in (EWITS, 2012), MN-IA (compared to ND-SD and Illinois) appears to be the most economical location to comply with the MISO renewable targets. Furthermore, these sensitivities help demonstrate that wind power output (i.e. capacity factor) is by far the most important driver of optimal siting decisions, and of our results. We continue to use 2006 as our base case sample year for wind since it provides the most conservative results for the break-even transmission cost premiums.
Wind capacity cost	For the base case, we assume that overnight installed capital costs for wind farms are $1,750/kW. Here we test installed costs of $1,500/kW and $2,000/kW. We find that the break-even transmission costs change by less than 10% for both MN-IA and ND-SD.
Reduction in market prices due to increased wind generation	Market prices and their marginal energy component (MEC) are likely affected by increased transmission capacity and/or wind generation on the grid. For example, (Woo et al., 2011) shows that LMP prices tend to decrease with increasing amounts of wind capacity in Texas (ERCOT). They estimate that a 10% increase in wind capacity leads to a 2% to 9% decrease in average LMP prices in ERCOT depending on the zone they considered. As of June 2014, there were about 13.4 GW of wind installed in MISO. For this analysis, we add about 10 GW of wind capacity to MISO to meet the 40 TWh policy target, a 75% increase in wind capacity. Therefore, we expect a decrease in market prices, perhaps by 15% to 70% if scaling the effects from (Woo et al., 2011) linearly. Although we do not endogenize this effect in our model, we run two alternative scenarios in which we scale MEC prices down by 15% and 70% to see the effect on the results. We find that the "15% scenario" reduces the estimated break-even transmission cost premium by 5%, and the "70% scenario" reduces it by 20%. This is unsurprising, as lower energy values partly eliminate the benefits of increased capacity factors in remote sites.
Capacity price ($/MW-day)	We test how a low price assumption ($17/ MW-day) affect the results compared to the base case assumption of $150/ MW-day. We find that with a lower capacity price, the competitiveness of some Illinois wind farms (the best ones) diminishes, and therefore remote wind farms in MN-IA and ND-SD become more competitive. Therefore, the transmission break-even cost premium for both MN-IA and ND-SD increase by about 20%.

SI4: Chapter 4

SI4-A: Demographics in Massachusetts

Table S2: Demographics for Gloucester and Rockport, and coastal Massachusetts counties.[1]

		Gloucester	**Rockport**	**Essex County**	**Plymouth County**	**Barnstable County**
Population		28,789	6,952	743,175	494,915	215,888
Age	<18	19%	17%	23%	24%	17%
	18-65	63%	60%	63%	62%	58%
	>65	18%	23%	14%	14%	25%
Gender	Female	54%	52%	52%	51%	52%
Median Income		$60,229	$70,288	$68,776	$75,816	$61,597
Education	B.A. earned	33%	50%	37%	34%	40%
Registered Party[2]	Democrat	29%	25%	33%	29%	26%
	Republican	10%	10%	12%	14%	16%
	Independent	61%	64%	55%	58%	57%

1. Data from (U.S. Census Bureau, 2016) ; 2. (2012)

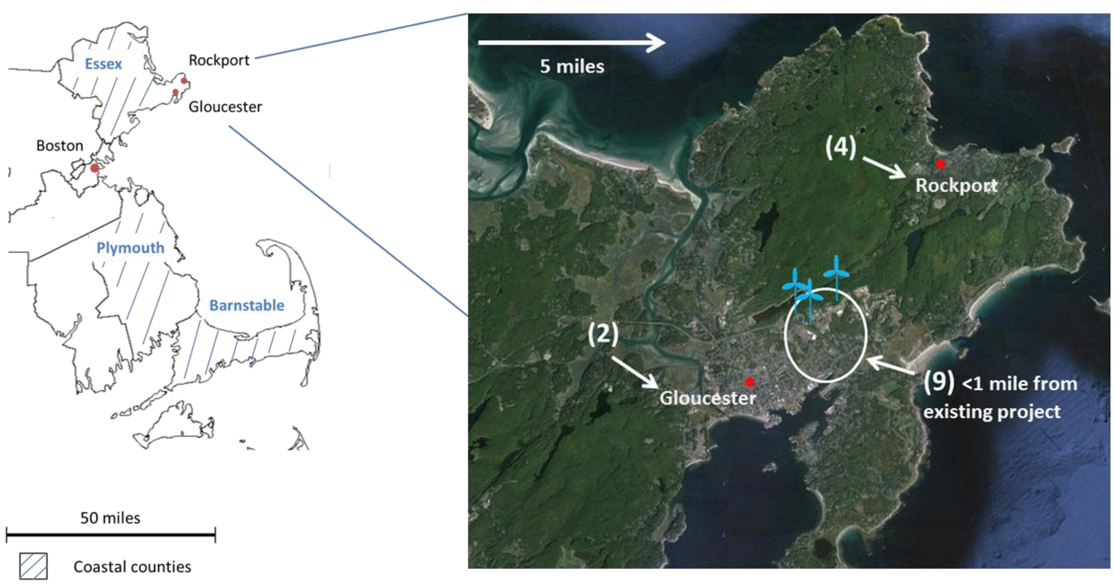


Figure S1: Left: Massachusetts Coast. Right: General location where the 15 interview participants live in Gloucester and Rockport.

SI4-B: Offshore image presented during the choice task

Figure S2: Example view of offshore wind project that is ~2 miles from shore in Great Yarmouth, England (Scroby Sands Wind Farm).

SI4-C: Interview questions

Part I: Verbal introduction of the interview process at beginning, after asking to sign consent form

I am a doctoral student at Carnegie Mellon University, and grew up around here (in Newburyport). I'm currently working on a study on energy that's part of my doctoral work. My work is funded by Carnegie Mellon University and by a fellowship by the Environmental Protection Agency.

I'll first ask you to tell me what you know about wind projects in your region. All the questions I'll ask you are meant to stimulate a discussion. Sometimes, I may repeat questions just so I can make sure I understand everything you say. Please don't worry about whether your answers are right or not, just tell me everything that comes to mind. At the end of these questions, I'll then ask you to take a very short survey that asks you to choose between several alternatives. Lastly, I'll provide you with a short demographic form to fill out.

The interview will take between 30 and 60 minutes. I'll cut it off at the 1 hour mark in case it goes over; however, if you'd like to continue and finish, it's up to you.

I will not include any directly identifiable information about you in any results or publications. Also, please do not discuss identifiable and sensitive information about third parties. I will be recording the conversation so that I can then summarize the results from our interview. I may want to use a short portion of any audio recording for illustrative reasons in presentations and publications of this work for scientific or educational purposes. In such cases, your name will NOT appear, nor any identifiable information.

- First, do you have any questions about this research?
- Do you agree to participate in the study?
- Do you allow me to audio record?
- Lastly, do you give permission to use portions of the audio recording for scientific / educational purposes?

OK, shall we begin?

Part II: Interview

1. Are you aware of any existing wind projects in your area?

2. Tell me a bit more about what you know about these wind projects
    a. Anything else?
    b. Are there other things you can think about related to these wind projects?
    c. What sort of information, if any, did you get about this project when it was being considered?
    d. Did you generally support the project?

3. Are there any specific aspects related to having these wind installations nearby that you feel very **POSITIVELY** about?
    a. You mentioned ______. Tell me more.
    b. Anything else related to ________ that you feel is important for us to talk about?
    c. Anything else?

4. Are there any specific aspects related to these existing wind installations nearby that you feel very **NEGATIVELY** about?
    a. You mentioned ________. Tell me a bit more about that.
    b. Anything else related to ________ that you feel is important for us to talk about?
    c. Anything else?

5. Are there other existing wind installations in the region that you are aware of, but that are not as near your house as the ones you just told me about?
    a. How do you feel about those?
    b. Overall, would you support have those project built?
    c. You mentioned ____________. Any other projects nearby that you are aware of? *(Go over questions a and b again for these new projects if the participant mentions any)*

6. Imagine that there is a **NEW** wind project that would be built **1 mile** from your house. What are positive aspects related with such projects in your view?
    a. You have mentioned ____________. Tell me more.
    b. You have also talked about ___________. Can you tell me more about that?
    c. Anything thing else?

7. What are some of the negative aspects related with such projects in your view?
    d. You have mentioned ____________. Tell me more.
    e. You have also talked about ___________. Can you tell me more about that?
    f. Anything thing else?

8. Overall, would you support having this project within **1 mile** of your home?

9. Now imagine that there is a **NEW** wind project that would be built **5 miles** from your house. How about you feel about the project?

10. Now imagine that there is a **NEW** wind project that would be built **offshore (like at sea, let's say 2 miles from the shore in ____**insert town name**___)**. How would you feel about the project?

11. Of all the characteristics you mentioned about the various hypothetical projects that we talked about (within 1 mile, 5 miles away, and offshore) can you please rank the characteristics that are most important to you?
    a. For example, you mentioned __________. *[Write each down and show them]*

    b. How would you rank these?

Part III: Choice question

A page with the pictures will be printed and shown to the participant in the in-person interviews. The pictures will vary depending on whether the participant lives in Gloucester or Rockport. For phone interviews, participants will be asked to login to their email and open the pictures for review.

1. The figures below show three options for wind projects that could be built in your area. Please describe to me your thoughts about these different options.
2. Tell me about these pictures, what do you see?
3. Do you know where that location is? Please explain further?
4. Where do you live in relation to the map?
5. Is this picture confusing at all, or does you understand it fine?

After showing all the pictures (*see* Table 4.1 in Chapter 4)

6. Which of these options do you prefer?
7. Why?
8. What other considerations come to your mind ?
9. RANKING: if you had to rank them, which one is best? Please rank them in order of best to worst. Why?

SI4-D: Project characteristic mapping

Table S3: List of the 55 wind project characteristics coded across all interviews and example quotes from interviews that were coded as a characteristic. These were aggregated into categories presented in Table 4.3 in Chapter 4.

Aggregated category	Project characteristic	Example quote
Visual	visual	There is a price to be paid for [a new wind project], in a place of great natural beauty, is the price too steep... I don't know
	landscape	It depends on placement. We like to go in the woods hiking so I wouldn't want it to be in the place we normally go hiking, and wreck that natural beauty landscape.
	ocean view	The ocean view ... It's our legacy, and I wouldn't want to have it spoiled anymore.
	orientation	I think [the expansion project would be] too much in a little area
	spinning	Some of [the existing turbines] don't run, other days they run, I don't exactly know how they work.
Climate change / renewable	energy problems	I understand that we need to find more of a creative long-term solution to solve our energy problems.
	oil dependence	I'm glad we're pursuing non-diesel energy sources.
	pollution	To me, [the existing wind project] is a positive... I know that we need to find a new energy, we can't go back to the old energy which was burning coal...with all these emissions, we'd be going blind, driving in the fog.
	renewable	I think the attempt to use a renewable clean energy resource is 1 commendable and 2 absolutely necessary
Economics	economics	I think I'd probably also ask what [the new wind project] is used to power for, because I have wondered that... or if it went straight to a power company, that would be great, and then got distributed to everyone, and lowered bills.
		I think [the existing wind project] is a great idea, it helps the town, which doesn't have a lot of money.
		If [a new wind project] going to save the city money, sure. And then where is that money savings going? I'd like to know, I don't know. I haven't seen anything produced on [the existing project]. Because, for example, if you noticed the road driving

		up here, it isn't very good.
	energy produced	The wider range it could provide power for, the better.
	intermittent energy	energy generated by wind turbines must be stored, it must be used immediately.
	little maintenance	there is no maintenance, I would imagine it would be low.
	longevity	I guess I would like to know the longevity of it? What's the maintenance schedule?
	property value	I think that all the lawyers who live in east Gloucester would be at arms, because I think [the offshore project option] would devalue their property.
	tourism	I think seeing wind turbines offshore might detract tourists.
Personal experience with wind	existing project	My experience with [the existing project] has been positive … [the turbines] are in my backyard and it's OK.
		[Expanding on the existing project] would probably work out well. The people aren't going to disagree with it too much because they are already there.
	accustomed to project	I would probably lean more towards the Gloucester option [since] people … are really used to seeing them.
	trust	What kind of trust was built from the [existing project]? Would they be using the same contractors [for the new project]? Using someone new? They will have to prove their trustworthiness if it's someone new.
Specific site	specific site	Well certainly the dump is not one of the most visually compelling places, which is good for a wind project.
	land use	I think about the land that has to be cleared for [a new wind project], and all of the other things that have to happen.
	location	[I'd want to know of the] location [of a new project] to make sure it wasn't in a historical area, or area that was not receptive to modern technology.
	populated area	The location [of the existing project] is not populated, there aren't any houses around there...it's not even in a residential area or anything like that. It isn't even an area that could potentially become a residential area.
Community identity	community identity	I think [the existing wind project] distinguishes Gloucester from other towns.
	community	our 5 year old grandson is in love with [the existing wind project]…every time he comes, we have to go stand at the base of the wind mill and look at up them.
	concerns for neighbor	How do my neighbors feel about it? Will it create controversy or rift in the community?
	future technology	My understanding is that [the existing project] was basically a test for wind turbine [technology]... and then the idea was to go far offshore where the wind was stronger and steadier.
	inspiration	I'm an artist so I'm not coming from the same place as other people might… [an offshore project would be] in my field of vision, in my field of inspiration … it would be more of a hot button for me [compared to an onshore project].
Local environment	environment	What effect will [a new wind project] have on the environment?
	ocean	I just think that the oceans are so fragile right now because of all the plastics, offshore drilling, I really don't think one more thing [like an offshore wind project] affecting it.
Noise and flicker effect	noise	I'd ask about the noise [regarding a new wind project within 1 mile of my home], because I don't know what it's like to live next to one.
	ocean noise	One of my favorite things about where I live is that I sleep to the sound of the ocean. I think I would be sad if the wind mills would be louder than the ocean.
	flicker effect	I've heard about the flicker effect, and people's nervous system is affected if the sun is in a particular position or whatever so that concerns me… I don't know any low level or any kind of direct injury I'm having from it now that I'm living

		in Gloucester.
Wildlife	wildlife	Is it displacing a whole bunch of animals, or general messing with the overall ecosystem?
	bird deaths	They said it was going to kill birds … so I got my [binoculars] and watched them … I haven't seen one bird dead yet.
	bat deaths	There are some data about wind farms in the Berkshires, and elsewhere, killing large numbers of bats. And bats are having big problems in a number of realms, which would be on the negative side of the ledger with any wind project.
	marine life	I'd be more concerned with the offshore because of the other impacts, like to the ocean life.
Proximity	NIMBY/ proximity	If [the new wind turbines] were sitting in my backyard, I might feel differently.
		Because [turbines are 5 miles away], they wouldn't be as much of an immediate concern for me.
		I'd probably like it a little better if [the project] was something along the horizon rather than being right outside [my home].
		That would be fine, [putting a new project in Rockport and not Gloucester], I mean that really doesn't affect me.
		Well I don't live [near the existing project], so I'm sure that the people that see it every day don't see it as pretty as I do.
Process / communication	communication	Is [the new wind project] something that someone is trying to shove down our throats? Or is there ability to negotiate and really get true reasonable conversation about it based on facts, based on realities … who's benefiting, what's going on behind the scenes?
	compromise	[Accepting a new wind project in our community] is not a case of surrender, it's a case of an armistice; an agreement - you get this, we get that. It's not a war.
	expansion	[Regarding the prospect of a three turbine project within a mile of my home], I would probably want to know if they were planning on expanding, making more.
	regret	Now that we have [the existing wind project], there doesn't seem to be recourse for what we do now.
	utility	I'm all for other sources of energy, solar… wind farms… stuff like that. Anything to get away from the oil, you know…and national grid (local utility).
	Who builds the project?	What's the history of these things? Are they using a reputable manufacturer? Did they do a study?
Size / number of turbines	number of turbines	I'd be all for [a new project within 1 mile of me], as long as there wouldn't be 20 more wind turbines to crowd out the sky. If it was a few more, I'd be totally all for it.
	size of turbines	How tall would they be? Comparable in height to what Gloucester has?
Safety / hazard	safety	Are the blades going to come tearing off?
	driving distraction	when you're driving through the highway, and then all of a sudden there are these three huge wind mills, you know they are a bit of a distraction on the road
	health	What is coming off of those things? Is it radiation? ... There's got to be something coming off of it. We don't know much about it, but maybe 50 years from now people will say that "you know those wind mills, well those cause cancer" or something wrong with your hearing, the closer you are to them.
	endurance with extreme weather	I'd be concerned with [offshore turbines] breaking away… the ocean is always in motion, especially with hurricanes… that would be my main concern.
	landmark	I'm able to know where I am in relation to the [existing] wind turbines, which I think is good.
	navigation	[an offshore project] would be cute, but you'd have to have a good light house so that ships wouldn't bump into them.
Construction	construction	How long would it take to finish putting everything up, and any kind of inconveniences like traffic rerouting?... How long would

		it take to complete?
Fishing	fishing/ fishermen	This is a very fishing dependent community... if you put them on the water, and you start running lines in the water, and you impact the fish population,... you're going to have a ton of really angry people.
Cape Wind	Cape Wind	It was quite an ambition project, a controversial project, a huge-scale project, that never came to fruition... ultimately the whole thing crashed... I can't imagine what the people in Cape Cod were thinking.

SI5: Chapter 5

SI5-A: Survey Samples

We recruited participants from the coastal Massachusetts sample in Gloucester and Rockport (MA sample) over a two week period through a combination of online advertising at a local newspaper (*Gloucester Times*), canvasing neighborhoods in the community, and advertising the survey at a booth in front of a local grocery store. In-person surveys were administered with a tablet. We recruited the broader U.S. sample from Amazon's Mechanical Turk (US sample). Overall, the survey took on average 12 minutes to complete and we compensated participants with a $5 Amazon gift card. In our final results, we excluded participants from the MA sample who did not live within either Gloucester or Rockport, and excluded participants in both samples who spent less than 5 minutes on the survey, since that was the minimum time that we (as the survey designers) took in fully answering all questions. This resulted in 192 participants from MA (out of 198 collected) and 318 from the US sample (out of 405 collected), or 2280 and 4470 observations respectively (# participants X 5 random choice tasks X 3 choices per task). Prior to administering the full survey, we tested the survey with a preliminary sample of 100 participants from the US sample and 5 participants from the MA community to fine-tune the survey contents.

Table S4 shows the demographics of the final samples used in this study. The MA sample has a larger portion of participants over the age of 65 (32%) than the US sample (2%), which is unsurprising since US participants tend to be young (Ipeirotis, 2010). In 2010 residents over 65 accounted for 18% of the population in Gloucester and 23% in Rockport (compared to 13% across the U.S. (U.S. Census Bureau, 2016)). We therefore have a slightly more elderly population in the MA sample than exists within

Gloucester and Rockport, likely because a large portion of our surveys were collected during working hours (54 out of 198) when retired individuals were more available to participate. From Table S4, we also observe that the MA sample had slightly higher household income with 27% of participants earning greater than $100,000, compared to 13% in the US sample, and compared to 24% across the U.S. (U.S. Census Bureau, 2016). Similarly, a larger portion of the MA sample earned a bachelor's degree than the US sample (61% compared to 49%). On the contrary, political affiliation and gender were fairly evenly distributed between the two samples. In our final model, we control for these demographic characteristics to see whether they affect wind project preferences, but largely find that they don't.

Table S4: Demographics of samples.

		MA	US
# in sample		192	318
Age	18-35	14%	56%
	35-65	46%	42%
	>65	32%	2%
	NA	8%	0%
Gender	Female	58%	47%
Income	<$35k	12%	30%
	$35-49k	6%	23%
	$50-74k	16%	24%
	$75-99k	11%	10%
	$100-150k	17%	10%
	$>150k	10%	3%
	NA	28%	<1%
Education	B.A. earned	61%	49%
Politics	Liberal	55%	51%
	Moderate	26%	23%
	Conservative	12%	21%
	NA	7%	5%

SI5-B: Utility function results

Table S5 shows the resulting coefficients for Model 1-3 for the coastal Massachusetts sample (MA) from Gloucester and Rockport, and Table S6 shows results for the U.S.-wide sample (US) from Amazon's Mechanical Turk. Below we describe the major findings from these models.

How important are economic benefits?

In all models for the MA sample (Table S5) and the US sample (Table S6), "Savings" and "Tax Revenue" have strong predictive power in learning whether a participant will choose a certain project. "Savings" is significant at 0.1% and "Tax Revenue =$500,000" is significant at 1% or lower. However, in Models 2 and 3 for both samples, "Tax Revenue = $250,000" is not significant, suggesting a non-linear trend in preferences for tax revenue. We also observe that the US sample has higher coefficient values for

"Savings" than the MA sample. For example, Model 2 for the MA sample has an average "Savings" coefficient of 0.1 compared to 0.4 in Model 2 for the US sample. This suggests that "Savings" played a larger role in helping US participants select a project compared to MA participants. A similar trend exists for the coefficient on "Tax Revenue=$500,000", which is approximately 2.0 in the MA sample compared to 3.0 in the US sample for Model 2. We also observe that tax revenue from the project adds even more utility when the project is located within a participant's hometown. This effect, captured by the interaction variable, "(Tax Revenue)*(Hometown)", is significant at 1% or lower across all models and both samples.

Is there a NIMBY effect?

We find that the preference for having a project within a participant's home community (as opposed to 80 miles away), captured by the "Hometown" variable, and the preference for having a project within 1 mile of their home, captured by the 'Hometown-1Mile" variable, are not significant for the MA sample (Table S5). There are only two cases in which the MA sample preferred a project 80 miles away. First, as noted in Model 3, if participants in the MA sample did *not* support wind energy development, then "Hometown" was significant at 0.1% with a negative average coefficient value of (-3.5). However, this effect disappears if the participant *does* generally support wind development, represented by the interaction term "(Support wind = yes) * (Hometown)", which is also significant at 0.1% and has a coefficient value of 3.1. This interaction term is only significant for the MA sample. Similarly, this preference is further weakened if MA participants agree that their community should help address climate change, represented in Model 3 with the interaction term "(Support CC= yes) *(Hometown)", which has an average coefficient value of 0.8 and is significance at 10%. Second, we also observe that MA participants who are new to the community (less than 10 years in Gloucester and Rockport) tend to prefer more distant projects. The coefficient value on the interaction term "(New to community) * (Hometown)" is significant at 1% with coefficient value (-0.6).

There is more evidence of NIMBY preferences for the U.S.-wide sample (Table S6). In Model 3, the "Hometown" variable is significant at 10% with an average coefficient value of (-0.7), but not in Models 1 or 2. Similarly, the variable "Hometown_1Mile" is significant at 5% in all models (-0.37 in Model 2). As shown in Model 3, we also find that US participants who identified with liberal politics are less opposed to a project within 1 mile of their home, noted by the interaction term "(Hometown-1Mile)*(Liberal)", which is significant at 5% with coefficient value 0.7. Similarly, those who support actions to reduce climate change have a higher preference for a project in their community, noted with the interaction term "(Support CC= yes) *(Hometown)", which has an average coefficient value of 0.6 and is significance at 10%.

Is there a preference for onshore vs. offshore?

Participants from both samples have a preference for onshore projects; however the effect is stronger with the MA sample. As noted in Table S5, the MA sample has significant coefficient values for "Onshore" at 0.1% across the three models. This preference is weaker for the US sample at 5% and 10% significance across models (Table S6). The coefficient value is also larger for the MA sample at 1.25 (0.1% significance) compared to 0.2 for the US sample (10% significance) in Model 2. We explore reasons for this difference in Section 5.2 of Chapter 5. We also find a slightly lower preference for onshore (more accepting of offshore) with younger MA residents, noted with the interaction term "Age<40" (average coefficient of (-1.0) with 5% significant, Model 3 in Table S5). However, we find no effect of age in the US sample. There is also a slight NIMBY effect regarding offshore projects for the US sample, who have a stronger preference for onshore if the project is located in their community, noted with the interaction term, "(Hometown) * (Onshore)", which is significant at 5% with an average coefficient value of 0.6, but not significant for the MA sample. Lastly, Rockport residents have a slightly lower preference for onshore than Gloucester residents, noted in the interaction term "(Rockport) * (Onshore)", which is significant in Model 3 at 5%, with a negative average coefficient value of (-0.65).

Table S5: Utility function model estimates for the Coastal Massachusetts (MA) sample.[10]

	Model 1		Model 2				Model 3			
	μ		μ		σ		μ		σ	
Savings (lognormal)	0.061	(0.006)***	0.099	(0.147)***	0.085	(0.16)***	0.087	(0.126)***	0.033	(0.197)…
TaxRev=250k (lognormal)	0.581	(0.168)***	0.965	(0.248)	0.112	(0.32)	0.967	(0.25)	0.077	(0.451)
TaxRev =500k (lognormal)	1.170	(0.16)***	1.965	(0.149)***	0.946	(0.127)***	1.860	(0.165)**	1.087	(0.152)***
Hometown	-0.090	(0.189)	-0.201	(0.266)	2.266	(0.277)***	-3.481	(0.563)***	1.385	(0.245)***
Hometown_1 Mile	0.017	(0.168)	0.123	(0.252)	0.894	(0.525)…	0.029	(1.116)	0.933	(0.667)
Onshore	0.707	(0.11)***	1.249	(0.181)***	1.640	(0.293)***	2.024	(0.551)***	1.235	(0.309)***
Onshore_Existing	0.248	(0.101)*	0.380	(0.14)**	0.346	(0.303)	0.342	(0.146)*	0.467	(0.316)
(Hometown) * (TaxRev = 250k)	0.863	(0.241)***	1.193	(0.349)***			0.993	(0.34)**		
(Hometown) * (TaxRev = 500k)	0.814	(0.237)***	1.101	(0.345)**			0.902	(0.335)**		
(Hometown) * (Onshore)							0.147	(0.276)		
(Age<40) * (Onshore)							-1.045	(0.426)*		
(Age<40) * (Hometown_1 Mile)							-0.682	(1.043)		
(Age<40) * (Hometown)							0.09	(0.381)		
(Support wind = yes) * (Onshore)							-0.55	(0.433)		
(Support wind = yes) * (Hometown_1 Mile)							0.379	(1.02)		
(Support wind = yes) * (Hometown)							3.144	(0.438)***		
(Support CC = yes) * (Onshore)							-0.625	(0.458)		
(Support CC = yes) * (Hometown_1 Mile)							-0.039	(1.007)		
(Support CC = yes) * (Hometown)							0.796	(0.435)…		
(Liberal) * (Onshore)							0.375	(0.313)		
(Liberal) * (Hometown_1 Mile)							-0.213	(0.571)		
(Liberal) * (Hometown)							0.309	(0.298)		
(High income) * (Onshore)							0.389	(0.329)		
(High income) * (Hometown_1 Mile)							-0.489	(0.602)		
(High income) * (Hometown)							0.278	(0.33)		
(Rockport=yes) * (Onshore)							-0.649	(0.295)*		
(Rockport=yes) * (Hometown_1 Mile)							-0.375	(0.564)		
(Rockport=yes) * (Hometown)							-0.150	(0.276)		
(new to community) * (Onshore)							0.624	(0.349)…		
(new to community) * (Hometown_1 Mile)							0.660	(0.725)		
(new to community) * (Hometown)							-0.888	(0.329)**		
Observations	2880		2880				2880			
log likelihood	-825	df=9	-765		df=16		-680		df=38	
AIC / BIC	1668 / 1722		1562 / 1658				1434 / 1652			

[10] Significance codes: ***= 0.1%, ** = 1%, * = 5%, … = 10%

Table S6: Utility function model estimates for the broader U.S. sample. [11]

	Model 1		Model 2				Model 3			
	μ		μ		σ		μ		σ	
Savings (lognormal)	0.113	(0.005)***	0.415	(0.045)***	1.239	(0.019)***	0.501	(0.038)***	1.782	(0.015)***
TaxRev=250k (lognormal)	0.882	(0.142)***	0.939	(0.199)	0.037	(0.287)	0.961	(0.194)	0.065	(0.281)
TaxRev =500k (lognormal)	1.595	(0.139)***	2.998	(0.136)***	4.439	(0.162)***	3.388	(0.135)***	5.905	(0.17)***
Hometown	0.171	(0.16)	0.077	(0.212)	1.330	(0.181)***	-0.713	(0.371)…	1.355	(0.188)***
Hometown_1 Mile	-0.257	(0.112)*	-0.369	(0.155)*	0.332	(0.398)	-1.140	(0.529)*	0.365	(0.4)
Onshore	0.211	(0.092)*	0.216	(0.122)…	0.179	(0.227)	0.556	(0.318)…	0.074	(0.242)
Onshore_Existing	0.092	(0.086)	0.159	(0.117)	0.047	(0.277)	0.180	(0.12)	0.049	(0.267)
(Hometown) * (TaxRev = 250k)	0.743	(0.202)***	1.179	(0.269)***			1.263	(0.273)***		
(Hometown) * (TaxRev = 500k)	0.721	(0.201)***	1.156	(0.259)***			1.237	(0.258)***		
(Hometown) * (Onshore)							0.558	(0.219)*		
(Age<40) * (Onshore)							-0.157	(0.218)		
(Age<40) * (Hometown_1 Mile)							-0.204	(0.331)		
(Age<40) * (Hometown)							-0.201	(0.229)		
(Support wind = yes) * (Onshore)							-0.46	(0.367)		
(Support wind = yes) * (Hometown_1 Mile)							0.75	(0.582)		
(Support wind = yes) * (Hometown)							0.225	(0.351)		
(Support CC = yes) * (Onshore)							0.069	(0.337)		
(Support CC = yes) * (Hometown_1 Mile)							-0.336	(0.508)		
(Support CC = yes) * (Hometown)							0.582	(0.319)…		
(Liberal) * (Onshore)							-0.343	(0.231)		
(Liberal) * (Hometown_1 Mile)							0.734	(0.341)*		
(Liberal) * (Hometown)							-0.324	(0.25)		
(High income) * (Onshore)							0.073	(0.34)		
(High income) * (Hometown_1 Mile)							-0.376	(0.504)		
(High income) * (Hometown)							0.182	(0.361)		
Observations	4770		4770				4770			
log likelihood	-1204	df=9	-1147		df=16		-1141		df=32	
AIC / BIC	2427 / 2485		2326 / 2429				2345 / 2552			

[11] Significance codes: ***= 0.1%, ** = 1%, * = 5%, … = 10%

SI5-C: Full survey – Massachusetts Coastal sample

Understanding perceptions of wind turbine projects

This survey is part of a research study conducted by Julian Lamy at Carnegie Mellon University and is funded by a Doctoral Fellowship Award by the U.S. Environmental Protection Agency.

The purpose of the study is to better understand people's perceptions about wind energy projects and where they are located.

Procedures

You will be asked to answer questions from an online survey. Most questions will require you to select between a few different alternatives of where to locate a hypothetical wind farm project. Each alternative will include different characteristics about it. In each question, these characteristics might change, but the objective is still the same, choose the one that you prefer based on the information provided. At the end of the survey, you will be asked to answer some basic demographic questions.

The survey takes between 5 and 10 minutes to complete.

Participant Requirements

In order to participate in the interview, you must be at least 18 years old.

Risks

The risks and discomfort associated with participation in this study are no greater than those ordinarily encountered in daily life or during casual conversation with your friends and family.

Breach of confidentiality is also a risk. Please refer to the Confidentiality section on how we will take every measure possible to protect your personal information (name, address, etc.).

Benefits

There will be no personal benefit from your participation in the study.

Compensation & Costs

For your time during the survey, you will be offered a $5 Amazon gift card. There will be no cost to you if you participate in this study.

Confidentiality

By participating in the study, you understand and agree that Carnegie Mellon may be required to disclose your consent form, data and other personally identifiable information as required by law, regulation, subpoena or court order. Otherwise, your confidentiality will be maintained in the following manner:

Your data and consent form will be kept separate. Your research data will be stored in a secure location on Carnegie Mellon property. Sharing of data with other researchers will only be done in such a manner that you will not be identified. By participating, you understand and agree that the data and information gathered during this study may be used by Carnegie Mellon and published and/or disclosed by Carnegie Mellon to others outside of Carnegie Mellon. However, your name, address, contact information and other direct personal identifiers will not be mentioned in any such publication or dissemination of the research data and/or results by Carnegie Mellon. Note that per regulation all research data must be kept for a minimum of 3 years.

All researchers involved in this study will take the following steps regarding each participant's identity: (1) Each participant will be assigned a number; (2) The researchers will record any data collected during the study by number, not by name; (3) Any original recordings or data files will be stored in a secured location accessed only by authorized researchers.

Right to Ask Questions & Contact Information
If you have any questions about this study, you should feel free to contact the Principal Investigator at:
Julian Lamy
202-257-8377, jlamy@andrew.cmu.edu
5000 Forbes Ave., Pittsburgh, PA, 15213

If you have questions pertaining to your rights as a research participant; or to report concerns to this study, you should contact the Office of Research integrity and Compliance at Carnegie Mellon University. Email: irb-review@andrew.cmu.edu . Phone: 412-268-1901 or 412-268-5460.

Voluntary Participation

Your participation in this research is voluntary. You may discontinue participation at any time during the research activity.

I am age 18 or older.
- Yes
- No

I have read and understand the information presented in this screen.
- Yes
- No

I want to participate in this research and continue with the survey.

- Yes
- No

What town do you live in?

- Gloucester
- Rockport
- Neither

0% 100%

Please select the region that you live in within Gloucester

- 1
- 2
- 3
- 4
- 5
- 6

0% 100%

Address

It's important to know your address because it helps the survey choose the right projects for you to evaluate

- OK
- I'd prefer not to share my address

0% 100%

What is your Street Address?

Zip Code?

0% 100%

Background Information:

A developer is to build a project consisting of 3 wind turbines somewhere in Massachusetts. They are considering different locations and sites, but the size (350 feet tall) and number of turbines (3 new ones) is the same for each project.

Below is a picture of the 3 existing wind turbines in Gloucester (from 500 feet away). You can assume that the new project would look similar to this one.

0% 100%

Your task is to choose the project you like best, each project will have different characteristics:

1) Location
2) Specific site in the location
3) Savings per month on your energy bill
4) Funds raised per year to the local government where the project is built

0% 100%

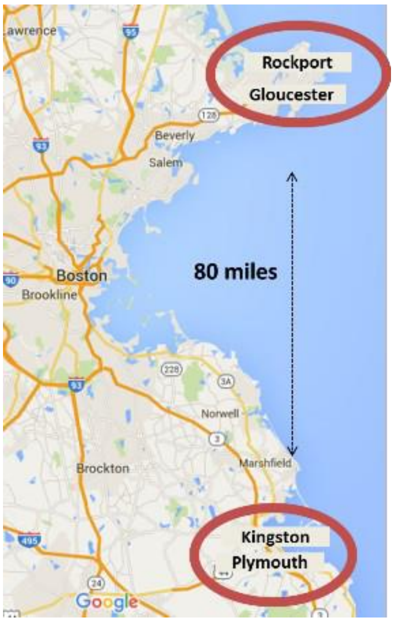
Please assume that all projects *:**

- Have NO impact to noise
- Have NO impact from shadow / flicker effect
- Have NO impact to birds, bats, or other wildlife
- Have NO impact to boating or navigation (offshore)
- Are safe and can withstand extreme weather events
- Produce the same amount of energy and emission reductions

**** State-of-the-art technology will be used to ensure these are true for each project considered*

0% 100%

The new wind project will be built within one of two locations:



0% 100%

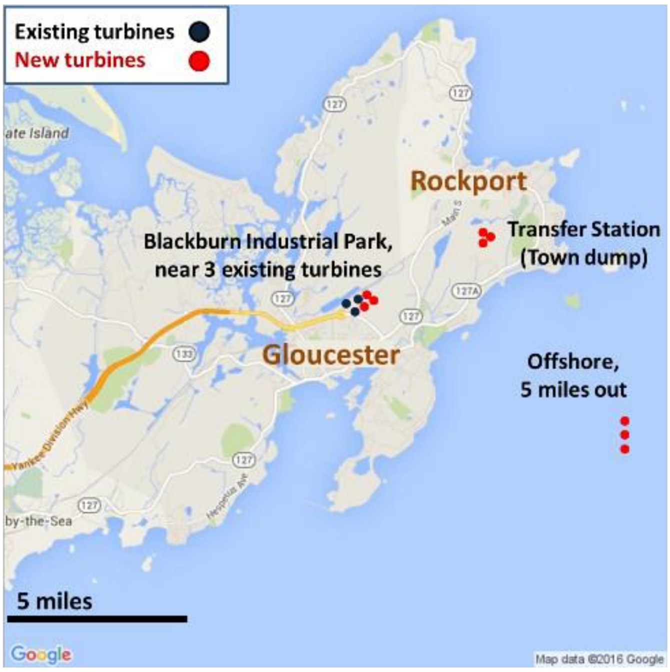
Here's an example of what the project might look like:

If Onshore (from 500 feet)...

If Offshore (5 miles from shore)...

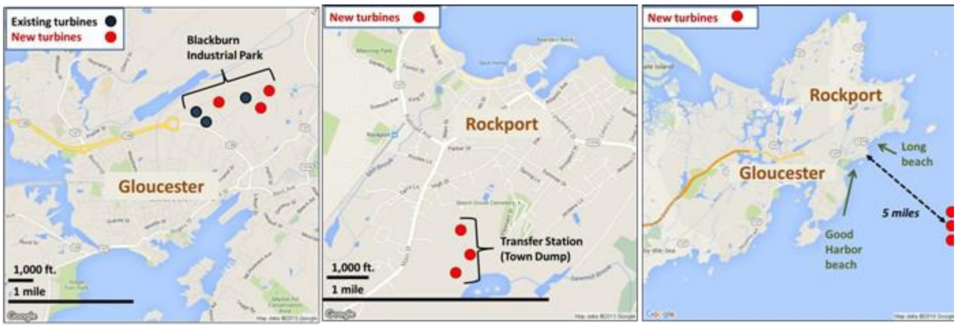
0% 100%

If in Gloucester / Rockport, the project would be built at one of the sites below:



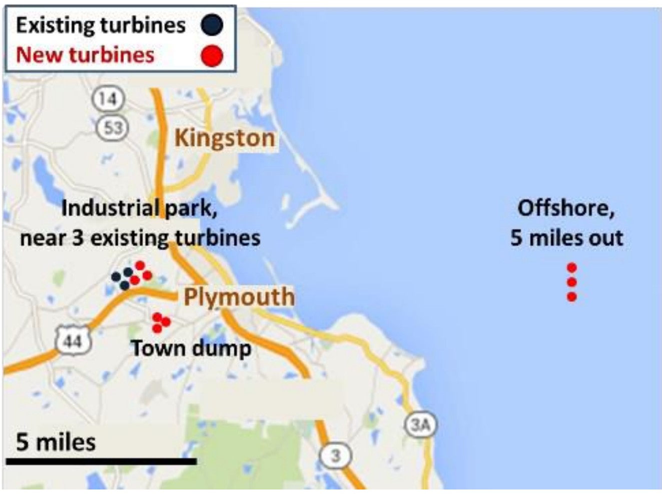
0% 100%

Here's a closer look at the possible sites if in Gloucester / Rockport



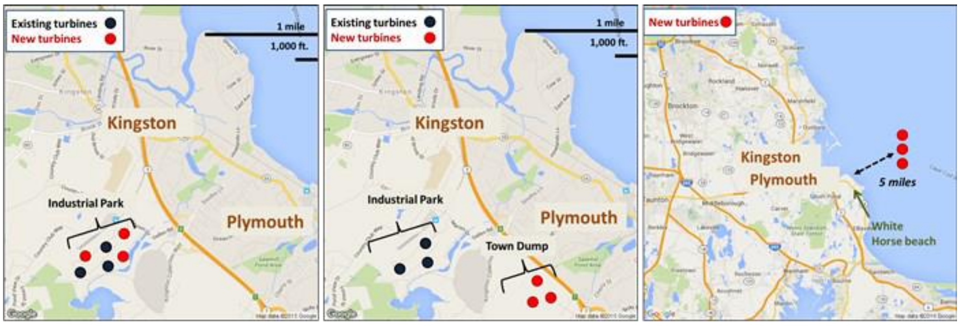
0% 100%

If in Kingston / Plymouth, the project would be built at one of the sites below:



0% 100%

Here's a closer look at the possible sites if in Kingston / Plymouth



0% 100%

Depending on the project, you may save $ each month

Even projects far away (like in Kingston / Plymouth) may affect your bill since the

0% 100%

Also, the project may raise funds for the local government

Please assume that:

- Funds will ONLY go to the government where the project is located
  - Either Gloucester/ Rockport **OR** Kingston/Plymouth
- If in Gloucester / Rockport, **BOTH** towns would share the funds equally. Similarly if in Plymouth/ Kingston.
- The funds would be used for programs **YOU** support. Examples could include:
  - Education, road repair, personal tax breaks, etc.

0% 100%

Here's a quick test to see if you understand these options

How many new wind turbines will be built for each option?

- ○ 1
- ○ 3
- ○ 2
- ○ 10

0% 100%

Sorry, incorrect!

Correct answer:

"3 new wind turbines"

Feel free to review the location and site descriptions on the previous pages by clicking the back arrow! You can do this at any time.

0% 100%

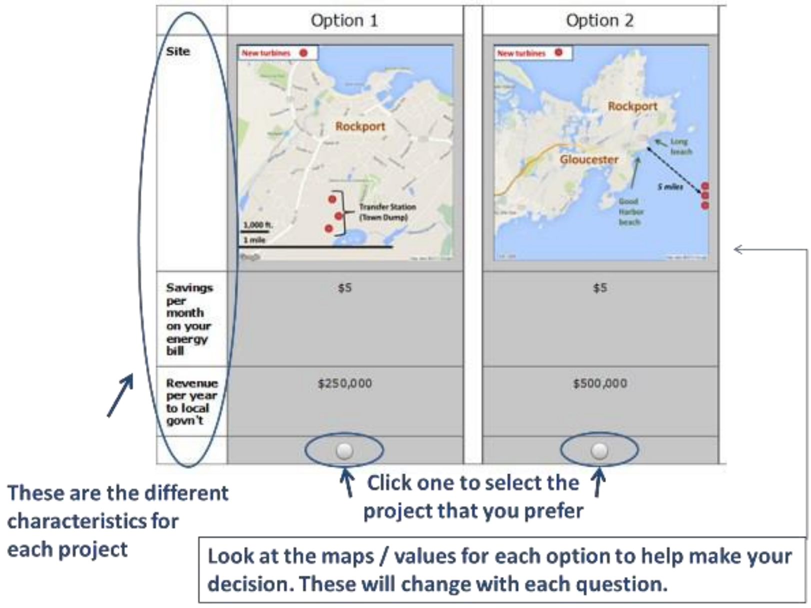
Correct!

0% 100%

Now, you will be asked 7 questions. Your task in each is to choose the wind project you prefer among those presented.

0% 100%

Here's an example:



0% 100%

Ready to begin? Click next

Use the back arrow anytime to review instructions

0% 100%

Choose the wind turbine project that you like best between those below.

(1 of 7)

	Option 1	Option 2	Option 3
Site			
Savings/ month on your energy bill	$0	$0	$20
Revenue per year to local govn't* **	$0	$500,000	$250,000
	○	○	○

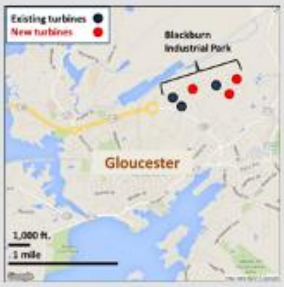
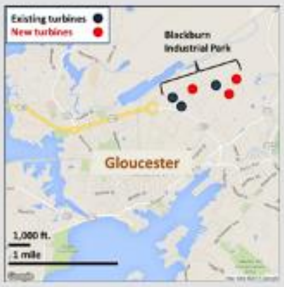
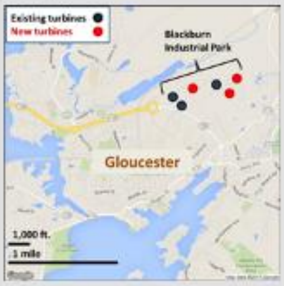
*** Funds to the local government are **ONLY** for the location in which the project is built: Gloucester / Rockport **OR** Kingston/Plymouth

Funds would be shared equally between the two towns in each location

0% 100%

Choose the wind turbine project that you like best between those below.

(2 of 7)

	Option 1	Option 2	Option 3
Site			
Savings/ month on your energy bill	$0	$5	$10
Revenue per year to local govn't* **	$0	$250,000	$500,000
	○	○	○

*** Funds to the local government are **ONLY** for the location in which the project is built: Gloucester / Rockport **OR** Kingston/Plymouth

Funds would be shared equally between the two towns in each location

0% 100%

Choose the wind turbine project that you like best between those below.

(3 of 7)

	Option 1	Option 2	Option 3
Site			
Savings/ month on your energy bill	$20	$10	$0
Revenue per year to local govn't***	$250,000	$500,000	$0
	○	○	○

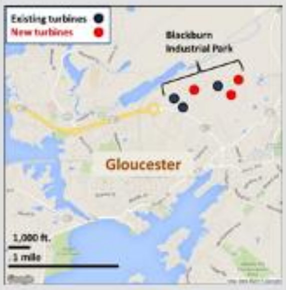
*** Funds to the local government are **ONLY** for the location in which the project is built: Gloucester / Rockport **OR** Kingston/Plymouth

Funds would be shared equally between the two towns in each location

0% 100%

Choose the wind turbine project that you like best between those below.

(4 of 7)

	Option 1	Option 2	Option 3
Site			
Savings/ month on your energy bill	$5	$5	$5
Revenue per year to local govn't***	$250,000	$250,000	$250,000
	○	○	○

*** Funds to the local government are **ONLY** for the location in which the project is built: Gloucester / Rockport **OR** Kingston/Plymouth

Funds would be shared equally between the two towns in each location

0% 100%

Choose the wind turbine project that you like best between those below.

(5 of 7)

	Option 1	Option 2	Option 3
Site			
Savings/ month on your energy bill	$5	$5	$0
Revenue per year to local govn't***	$500,000	$0	$250,000
	○	○	○

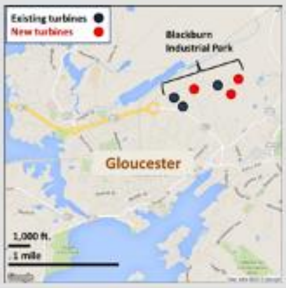
*** Funds to the local government are **ONLY** for the location in which the project is built: Gloucester / Rockport **OR** Kingston/Plymouth

Funds would be shared equally between the two towns in each location

0% 100%

Choose the wind turbine project that you like best between those below.

(6 of 7)

	Option 1	Option 2	Option 3
Site			
Savings/ month on your energy bill	$10	$5	$10
Revenue per year to local govn't***	$250,000	$500,000	$0
	○	○	○

*** Funds to the local government are **ONLY** for the location in which the project is built: Gloucester / Rockport **OR** Kingston/Plymouth

Funds would be shared equally between the two towns in each location

0% 100%

Choose the wind turbine project that you like best between those below.

(7 of 7)

	Option 1	Option 2	Option 3
Site			
Savings/ month on your energy bill	$20	$10	$10
Revenue per year to local govn't***	$0	$250,000	$500,000
	○	○	○

*** Funds to the local government are **ONLY** for the location in which the project is built: Gloucester / Rockport **OR** Kingston/Plymouth

Funds would be shared equally between the two towns in each location

0% 100%

Please rank the following factors in how important they were in helping you decide between projects

1 = most important ... 5 = least important

- [ ] distance from my home to the new project
- [ ] next to an existing wind project
- [ ] offshore (at sea) versus onshore
- [ ] savings per month on my energy bill
- [ ] tax revenue to the local govn't

0% 100%

How much would you pay each month to AVOID having a new 3 turbine wind project built within the following distances from your home?

$ per month

1 mile [ ]

5 miles [ ]

80 miles [ ]

0% 100%

How much did you think about these factors when answering the questions?:

noise impacts / flicker effect

- I didn't consider this at all
- not very much
- somewhat
- very much
- I considered this a lot

wildlife impacts (i.e., birds)

- I didn't consider this at all
- not very much
- somewhat
- very much
- I considered this a lot

0% 100%

A new wind project would fit well within the Gloucester/ Rockport community

- strongly agree
- agree
- neither agree nor disagree
- disagree
- strongly disagree

0% 100%

Climate change is an important problem that my community should help address

- strongly agree
- agree
- neither agree or disagree
- disagree
- strongly disagree

I generally support wind power development

- strongly agree
- agree
- neither agree or disagree
- disagree
- strongly disagree

0% 100%

Last Part: Demographic Questions
Almost done!

0% 100%

How long have you been a member of the Gloucester/ Rockport community?

- less than a year
- 1 to 3 years
- 3 to 5 years
- 5 to 10 years
- 10 to 20 years
- over 20 years

0% 100%

How many of your friends or family members live in Kingston / Plymouth?

- none
- very few
- some
- many

How many of your friends or family members live in Gloucester/ Rockport?

- none
- very few
- some
- many

0% 100%

Gender

- female
- male

Age

0% 100%

Which statement best describes your housing situation?

- I own my home
- I rent my home
- neither

What is the approximate value of your home?

- I don't own the home
- Less than $100,000
- $100,000 – $199,999
- $200,000 – $299,999
- $300,000 – $399,999
- $400,000 – $499,999
- More than $500,000

0% 100%

Household income range

- Less than $35,000
- $35,000-$49,999
- $50,000-$74,999
- $75,000-99,999
- $100,000-$150,000
- Greater than $150,000

What is the highest level of education that you achieved?

- High school graduate
- Some college, no degree
- Associate's degree
- Bachelor's degree
- Master's degree
- Doctoral degree

0% 100%

What is your occupation?

How would you describe your politics?

- very liberal (left wing)
- liberal
- moderate
- conservative
- very conservative (right wing)
- No affiliation / I don't care

0% 100%

Please enter your email below so we can send you a $5 Amazon gift card!

0% 100%

Do you have any comments about the survey?

0% 100%

All done,
Thanks for taking the survey!

If you have any questions or comments, do not hesitate to contact Julian Lamy at jlamy@andrew.cmu.edu or at 202-257-8377

Powered by Sawtooth Software, Inc.

0% 100%

SI5-D: Full surveys – U.S.-wide sample

Understanding perceptions of wind turbine projects

This survey is part of a research study conducted by Julian Lamy at Carnegie Mellon University and is funded by a Doctoral Fellowship Award by the U.S. Environmental Protection Agency.

The purpose of the study is to better understand people's perceptions about wind energy projects and where they are located.

Procedures

You will be asked to answer questions from an online survey. Most questions will require you to select between a few different alternatives of where to locate a hypothetical wind farm project. Each alternative will include different characteristics about it. In each question, these characteristics might change, but the objective is still the same, choose the one that you prefer based on the information provided. At the end of the survey, you will be asked to answer some basic demographic questions.

The survey takes between 5 and 10 minutes to complete.

Participant Requirements

In order to participate in the interview, you must be at least 18 years old.

Risks

The risks and discomfort associated with participation in this study are no greater than those ordinarily encountered in daily life or during casual conversation with your friends and family.

Breach of confidentiality is also a risk. Please refer to the Confidentiality section on how we will take every measure possible to protect your personal information (name, address, etc.).

Benefits

There will be no personal benefit from your participation in the study.

Compensation & Costs

For your time during the survey, you will be offered $1 through MTurk. There will be no cost to you if you participate in this study.

Confidentiality

By participating in the study, you understand and agree that Carnegie Mellon may be required to disclose your consent form, data and other personally identifiable information as required by law, regulation, subpoena or court order. Otherwise, your confidentiality will be maintained in the following manner:

Your data and consent form will be kept separate. Your research data will be stored in a secure location on Carnegie Mellon property. Sharing of data with other researchers will only be done in such a manner that you will not be identified. By participating, you understand and agree that the data and information gathered during this study may be used by Carnegie Mellon and published and/or disclosed by Carnegie Mellon to others outside of Carnegie Mellon. However, your name, address, contact information and other direct personal identifiers will not be mentioned in any such publication or dissemination of the research data and/or results by Carnegie Mellon. Note that per regulation all research data must be kept for a minimum of 3 years.

All researchers involved in this study will take the following steps regarding each participant's identity: (1) Each participant will be assigned a number; (2) The researchers will record any data collected during the study by number, not by name; (3) Any original recordings or data files will be stored in a secured location accessed only by authorized researchers.

Right to Ask Questions & Contact Information
If you have any questions about this study, you should feel free to contact the Principal Investigator at:
Julian Lamy
202-257-8377, jlamy@andrew.cmu.edu
5000 Forbes Ave., Pittsburgh, PA, 15213

If you have questions pertaining to your rights as a research participant; or to report concerns to this study, you should contact the Office of Research integrity and Compliance at Carnegie Mellon University. Email: irb-review@andrew.cmu.edu . Phone: 412-268-1901 or 412-268-5460.

Voluntary Participation

Your participation in this research is voluntary. You may discontinue participation at any time during the research activity.

I am age 18 or older.

Yes
No

I have read and understand the information presented in this screen.

Yes
No

I want to participate in this research and continue with the survey.

- Yes
- No

What state do you live in?

- Alabama
- Alaska
- Arizona
- Arkansas
- California
- Colorado
- Connecticut
- Delaware
- District of Columbia
- Florida
- Georgia
- Hawaii
- Idaho
- Illinois
- Indiana
- Iowa
- Kansas
- Kentucky
- Louisiana
- Maine
- Maryland
- Massachusetts
- Michigan
- Minnesota
- Mississippi
- Missouri
- Montana
- Nebraska
- Nevada
- New Hampshire
- New Jersey
- New Mexico
- New York
- North Carolina
- North Dakota
- Ohio
- Oklahoma
- Oregon
- Pennsylvania
- Rhode Island
- South Carolina
- South Dakota
- Tennessee
- Texas
- Utah
- Vermont
- Virginia
- Washington
- West Virginia
- Wisconsin
- Wyoming

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0% 100%

City?

Zip Code?

0% 100%

Background Information:

A developer is to build a project consisting of 3 wind turbines. They are considering different locations and sites, but the size (350 feet tall) and number of turbines (3 new ones) is the same for each project.

Below is a picture of 3 existing wind turbines from 500 feet away. You can assume that the new project would look similar to this one.

0% 100%

Your task is to choose the project you like best, each project will have different characteristics:

1) Town
2) Specific site in the town
3) Savings per month on your energy bill
4) Funds raised per year to the local government where the project is built

0% 100%

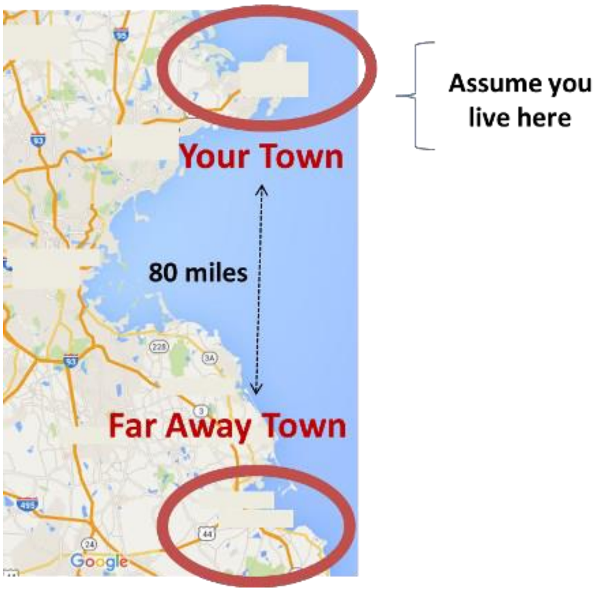
Please assume that all projects *:**

- Have NO impact to noise
- Have NO impact from shadow / flicker effect
- Have NO impact to birds, bats, or other wildlife
- Have NO impact to boating or navigation (offshore)
- Are safe and can withstand extreme weather events
- Produce the same amount of energy and emission reductions

**** State-of-the-art technology will be used to ensure these are true for each project considered*

0% 100%

The new wind project will be built within one of two locations:



0% 100%

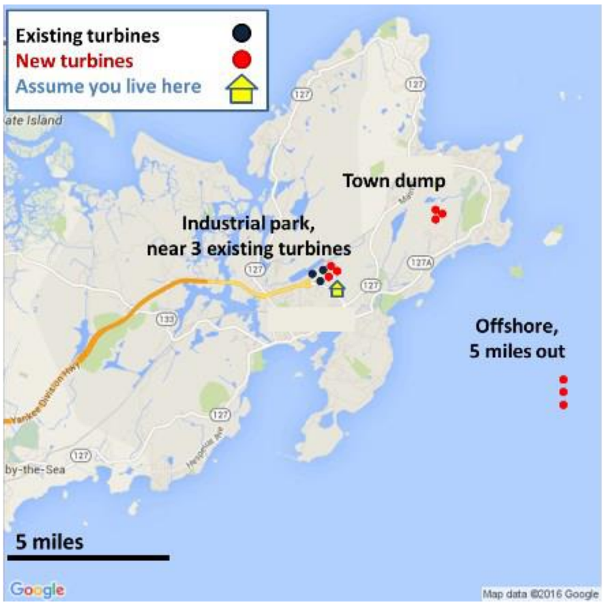
Here's an example of what the new project might look like:

If Onshore (from 500 feet)...

If Offshore (5 miles from shore)...

0% 100%

If in "Your Town", the new project would be built at one of the following sites:



0% 100%

Here's a closer look at the possible sites if in "Your Town"

0% 100%

If in the "Far Away Town" (80 miles), the new project would be built at one of the following sites:

0% 100%

Here's a closer look at the possible sites if in the "Far Away Town" (80 miles)

0% 100%

Depending on the project, you may save $ each month

Even projects far away may affect your bill since the electricity grid is interconnected

0% 100%

Also, the project may raise funds for the local government

Please assume that:

- Funds will ONLY go to the government where the project is located
  - Either in "Your Town" **OR** the "Far Away Town"
- The funds would be used for programs **YOU** support. Examples could include:
  - Education, road repair, personal tax breaks, etc.

0% 100%

Here's a quick test to see if you understand these options

How many new wind turbines will be built for each option?

- 1
- 3
- 2
- 10

0% 100%

Sorry, incorrect!

Correct answer:

"3 new wind turbines"

Feel free to review the location and site descriptions on the previous pages by clicking the back arrow! You can do this at any time.

0% 100%

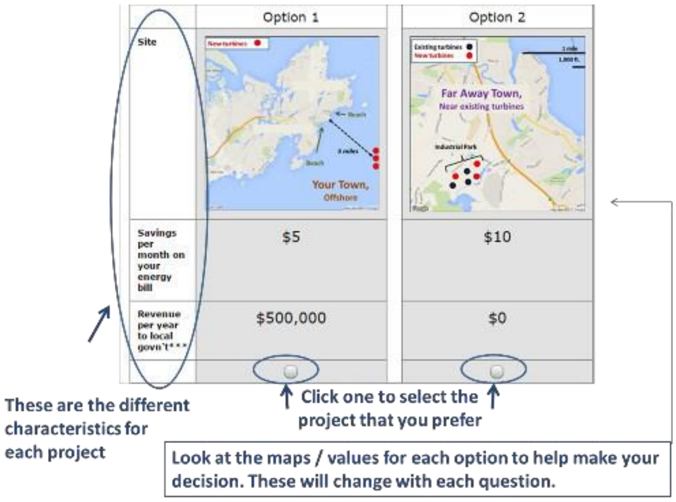
Correct!

0% 100%

Now, you will be asked 7 questions. Your task in each is to choose the wind

0% 100%

Here's an example:



0% 100%

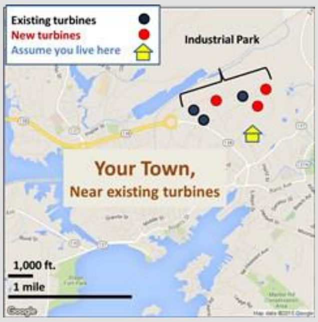
Ready to begin? Click next

Use the back arrow anytime to review instructions

0% 100%

Choose the wind turbine project that you like best between those below.

(1 of 7)

	Option 1	Option 2	Option 3
Site			
Savings per month on your energy bill	$5	$0	$20
Revenue per year to local govn't***	$0	$250,000	$250,000
	○	○	○

*** Revenue to the local government is **ONLY** for the town in which the project is built.

0% 100%

Choose the wind turbine project that you like best between those below.

(2 of 7)

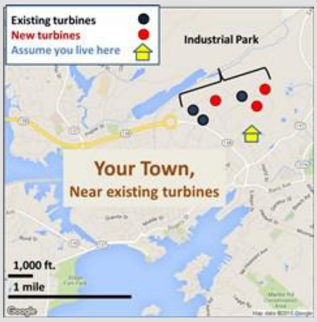
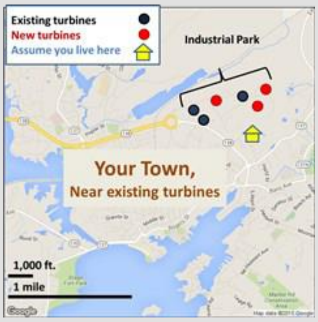
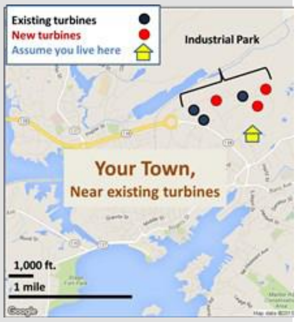
	Option 1	Option 2	Option 3
Site			
Savings per month on your energy bill	$0	$10	$20
Revenue per year to local govn't* **	$0	$500,000	$500,000
	○	○	○

*** Revenue to the local government is **ONLY** for the town in which the project is built.

0% 100%

Choose the wind turbine project that you like best between those below.

(3 of 7)

	Option 1	Option 2	Option 3
Site			
Savings per month on your energy bill	$0	$5	$20
Revenue per year to local govn't* **	$0	$250,000	$500,000
	○	○	○

*** Revenue to the local government is **<u>ONLY</u>** for the town in which the project is built.

0% 100%

Choose the wind turbine project that you like best between those below.

(4 of 7)

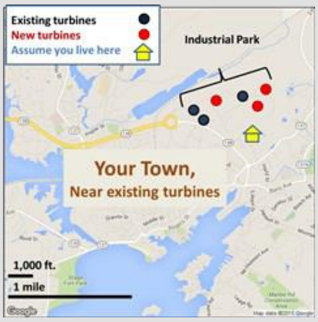
	Option 1	Option 2	Option 3
Site			
Savings per month on your energy bill	$20	$5	$10
Revenue per year to local govn't* **	$0	$500,000	$250,000
	○	○	○

*** Revenue to the local government is **<u>ONLY</u>** for the town in which the project is built.

0% 100%

Choose the wind turbine project that you like best between those below.

(5 of 7)

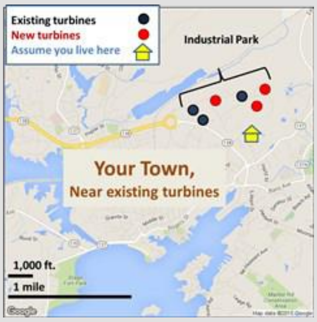
	Option 1	Option 2	Option 3
Site			
Savings per month on your energy bill	$0	$5	$10
Revenue per year to local govn't* **	$250,000	$500,000	$250,000
	○	○	○

*** Revenue to the local government is **ONLY** for the town in which the project is built.

0% 100%

Choose the wind turbine project that you like best between those below.

(6 of 7)

<table>
<tr><th></th><th>Option 1</th><th>Option 2</th><th>Option 3</th></tr>
<tr><td>Site</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Savings per month on your energy bill</td><td>$5</td><td>$5</td><td>$5</td></tr>
<tr><td>Revenue per year to local govn't***</td><td>$250,000</td><td>$250,000</td><td>$250,000</td></tr>
<tr><td></td><td>○</td><td>○</td><td>○</td></tr>
</table>

*** Revenue to the local government is **ONLY** for the town in which the project is built.

0% 100%

Choose the wind turbine project that you like best between those below.

(7 of 7)

	Option 1	Option 2	Option 3
Site			
Savings per month on your energy bill	$5	$0	$20
Revenue per year to local govn't* **	$0	$500,000	$500,000
	○	○	○

*** Revenue to the local government is **ONLY** for the town in which the project is built.

0% 100%

Please rank the following factors in how important they were in helping you decide between projects

1 = most important ... 5 = least important

- [ ] distance from my home to the new project
- [ ] next to an existing wind project
- [ ] offshore (at sea) versus onshore
- [ ] savings per month on my energy bill
- [ ] tax revenue to the local govn't

0% 100%

How much would you pay each month to AVOID having a new 3 turbine wind project built within the following distances from your home?

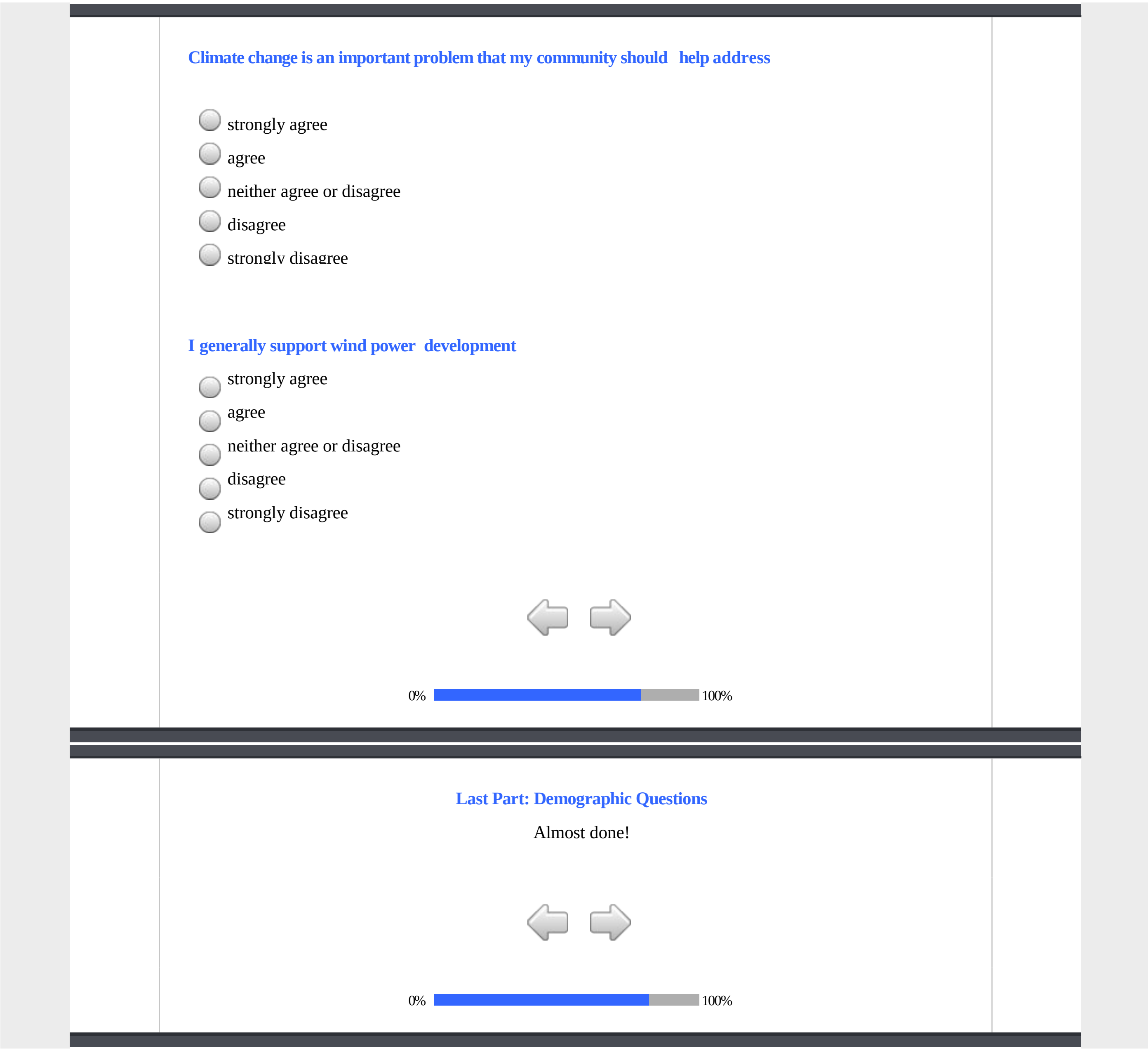
$ per month

1 mile [ ]

5 miles [ ]

80 miles [ ]

0% 100%



Climate change is an important problem that my community should help address

- strongly agree
- agree
- neither agree or disagree
- disagree
- strongly disagree

I generally support wind power development

- strongly agree
- agree
- neither agree or disagree
- disagree
- strongly disagree

0% 100%

Last Part: Demographic Questions

Almost done!

0% 100%

The rest of the survey is exactly the same as the one for the coastal Massachusetts sample (see Section SI5-C)