Title: Investment cost and view damage cost of siting an offshore wind farm: a spatial analysis of Lake Michigan

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Abstract

Investment and view damage costs are important determinants in siting locations for offshore wind farms (OWF) in the Lake Michigan region. This study is limited to the Michigan state boundary for the OWF sites and viewshed impacts. Investment cost depends on the depth and distance to shore of the farm. View damage cost depends on household density and consumer willingness to pay to avoid the visual disamenity of wind turbines. Both these costs are dependent on the geographic location and are summed to create an aggregate cost. Using ArcGIS, the OWF siting locations was mapped, with spatial analysis revealing the northern region of the lake at the minimum aggregate cost. The view damage cost contributes at most 68%, but on average 7%, to the aggregate cost. The aggregate levelized cost of energy (LCOE) ranges from 183 to 368 \$/MWh (average of 256 \$/MWh). The view damage LCOE contribution to the aggregate LCOE is 3% on average and 46% at most. View damage impact is the dominating factor only around a small shoreline region (due to large impacted populations). A series of maps are presented that highlight the investment and view damage tradeoffs which can inform OWF siting in Lake Michigan.

Keywords: Wind power generation, viewshed, willingness-to-pay, levelized cost of electricity, Great Lakes, ArcGIS

Abbreviations:

LCOE – Levelized Cost of Energy

O&M – Operations and Maintenance

OWF – Offshore Wind Farm(s)

WTA – Willing(ness) to Accept

WTP – Willing(ness) to Pay

1. Introduction

Wind energy is becoming one of the fastest growing renewable energy technologies with 45 GW of wind power added globally in 2012, which represented 15.9 percent of the world's total capacity additions [1]. Over 1.1 GW (2.4%) of the 45 GW increase was from offshore wind power [2]. For the United States, 13 GW of wind power was added in 2012, none of which came from offshore wind power sources [3].

The U.S. Department of Energy has invested \$227 million in offshore wind projects and research since 2011 [3]. These development projects range from the East Coast (where there is minimal space for onshore wind potential, but high demand for energy), the Gulf of Mexico (where there are many ports available for constructing large offshore wind structures, and Oregon (where the technology of floating wind turbine foundations can make offshore wind a reality for this deep coast area) [3]. These unique constraints and benefits highlight the many opportunities for innovation in supporting offshore wind in the U.S. In the Great Lakes, there are significant benefits due to shallow lake depths and high wind speeds close to the power demand areas. However, there are also disadvantages and constraints such as strong local opposition, ice effects on turbine and foundation structures, and existing policy and environmental regulations for Lake development.

Since none of the Great Lakes offshore wind energy potential is currently under development, this paper looks at the tradeoffs in siting offshore wind farm (OWF) locations in the Lake Michigan region. Specifically, the Michigan governed portion of Lake Michigan. The resulting framework can be used to inform future development. Typical siting practices used by project developers' look solely at maximizing the energy generation capabilities (high wind speeds) and minimizing the project costs (low depths) while abiding by the local laws/regulations. They then rely on public outreach and community engagement to address any social objections throughout the process [4]. In this case, the viewshed is not considered a separate cost, but rather a factor to be aware of. While other similar studies that analyzed OWF siting in economic valuation terms (such as in the Korean peninsula [5]), social viewshed impacts (such as in Delaware [6]), or spatial GIS integration (such as in Greece [7]), a similar analysis has not been done in Lake Michigan. This paper instead looks at the view damage cost as a separate tradeoff with equal consideration as power generation or economic costs.

One example of a siting assessment is the Report of the Michigan Great Lakes Wind Council, which defines favorable and unfavorable Michigan locations based on existing uses, state and federal laws, and environmentally excluded areas [8]. The results of this are presented in Fig. 1. An example of a proposed project was Scandia Wind's Aegir Project, which proposed placing two 500 MW wind farms 4-6 miles off the coast of Muskegon and Ottawa counties in Lake Michigan [9]. However, the local residents believed the turbines would dramatically alter the view and be detrimental to their way of life, so they voted against the installation thereby leading to project cancellation [10]. The project would have had significant societal benefits such as over 3,000 new (temporary) jobs and cleaner air quality due to displacing polluting energy sources [9]. Ultimately, perception of the view damage cost ended up derailing the project. View damage cost characterization will need to be incorporated sufficiently into current siting practices to make OWF projects successful in the Great Lakes.

[insert Fig 1 here]

Fig. 1: Lake Michigan offshore wind siting representing favorable locations ≤ 45 m depth, ≥ 20 sq mile (52 sq km) and defined as “categorically excluded, conditional, and most favorable” (figures from Klepinger [8])

This paper develops a spatial modeling framework to quantify tradeoffs between investment cost and view damage cost in OWF development in the Lake Michigan region. These costs will also be leveled by the power generation to provide comparable cost of energy results throughout the region. This analysis will enable quantitative consideration of viewshed in OWF siting and also allow a comparison of its importance relative to investment cost. This spatial assessment will be similar to the maps from the Great Lakes Wind Council report with the final results visually portrayed as a series of maps categorizing the investment cost, view damage cost, and the summation of those costs (defined as aggregate cost) [8]. This siting location analysis will also show whether investment cost or view damage cost is more influential in determining the lowest cost siting locations. This analysis can also inform potential policy changes in the state of Michigan.

2. Methodology

For this analysis, ArcGIS was used to compute and display the investment cost, view damage cost, and wind power generation as spatial models used in offshore wind turbine siting in Lake Michigan. The investment model and view damage model represent the calculated cost, while the wind power generation model represents the power generation. In the models, sites defined by geographic location (latitude and longitude) are analyzed to determine the minimum cost location which are influenced by several factors. Geographical data such as bathymetry (lake depth), land elevation, and spatial data contribute to the investment and view damage models [11]. Additional census factors include household count data by county and land use data analyzed with the viewshed survey data for the view damage cost model formulation [12]. Data on wind speeds are combined with the power generation curves as the factors used to create the wind power generation model [13].

The models also include assumptions (fixed parameters independent of location) to define the model scope. Each model consists of 100 3MW Vestas V112 turbines (300 MW OWF) oriented as a 10x10 grid with the spacing of 4 diameter lengths from north to south and 7 diameter lengths from west to east [14] [15]. This layout is a standard placement to minimize wake effects [16] (wind turbulence of one turbine affecting the downwind turbine) assuming the direct wind flow direction would come from west to east, which is the predominant wind direction in the winter when the winds are the strongest in Lake Michigan [17]. This model focuses on the spatial derivation of costs and minimizing these costs, so typical siting constraints such as shipping lanes and migratory pathways are not modeled. This allows decision makers to view unconstrained results, and it may serve to influence broader policy initiatives.

The sections below describe how the data are used to model investment cost, view damage cost, and wind power generation. The modules defining the factors and processes used to create the models are in Appendix A.

2.1. Investment cost modeling

The investment cost model is based on a similar model developed by Dicorato, which included installation, port, and transportation costs [18]. This includes wind turbine, foundation, collection system, transmission, integration system, grid interface, and development costs. Costs not included were operations and maintenance (O&M – including labor, equipment, and facilities), land lease cost, and replacement parts cost over the lifespan of the farm. These costs can account for 20% - 30% of the total lifecycle cost [13]. The factors in the model were bathymetry of the OWF location (d ; [m]) and least cost path distance following the lake bed between the farm and the Michigan shoreline ($D_{bathdist}$; [km]) as seen in Fig. 2. The $D_{bathdist}$ factor was calculated using ArcGIS based on d and the view distance between the farm to the Michigan shoreline ($D_{farmtoshore}$; [km]). These three factors are fundamentally dependent on the geographic location.

[insert Fig 2 here]

Fig. 2: Distance and depth/bathymetry factors in the investment cost model (not to scale)

Following the Dicorato model involved including a fixed exchange rate from euros to U.S. dollars which was €1:\$1.4 based on the 2009 data in the Dicorato model [18] [19]. This cost is converted to 2014 dollars (\$1 in 2009 becomes \$1.11 in 2014) to account for inflation [20]. The investment cost model was simplified by the assumptions made in Dicorato, such as parallel AC connections between turbines for the transmission configuration [18]. This cost was then calculated for the entire Lake Michigan region in ArcGIS. The investment cost [2014\$mill USD] can be expressed in Eq. 1 below as a function of the factors described above (d and $D_{bathdist}$) and the cost breakdown in the appendix. Ultimately all the factors in the investment cost equation are dependent on the geographic location.

$$Investment\ Cost = 815 + (4.84 * d) + (1.95 * D_{bathdist}) + (2.24 * D_{shoretoTS}) \quad (1)$$

The onshore transmission cost, which is a function of shoreline to transmission substation distance ($D_{shoretoTS}$; [km]), was neglected here due to the difficulty and variability in siting substations. These costs are neglected for this part of the investment cost model, but they can potentially range from 1% to 10% of the total investment cost (depending on depth and distance to shore) and was included in the levelized cost of electricity (LCOE) model [18].

The investment LCOE was determined based on the Tegan 2013 NREL definition of cost of wind energy with the definition shown in Eq. 2a and 2b [21]. Additional costs were added to the investment cost to be comparable with industry LCOE values. An increase of 9% was applied to the investment cost to account for onshore transmission (T_c), and a fixed annual operating expense (AOE) of \$136 per kW/yr (\$40.8 mill for the 300 MW farm) was applied at all locations for the land lease, O&M, and replacement parts cost [21]. A fixed charge rate (FCR) was computed, using a 10% prime interest rate (r) and 20 year life span (n), to represent the annual cost of debt servicing for the upfront investment cost. This was based on the Tegan 2013 NREL report using a FCR of 11.7% as shown in Eq. 2a [21]. The calculated net annual energy production [GWh/yr] is discussed in section 2.3. The final investment LCOE [\$ /MWh] is

determined using the *Annual Energy Production (net)* from the wind power generation model and is shown in Eq. 2b.

$$FCR = \frac{r(1+r)^n}{(1+r)^n - 1} = 11.7\% \quad (2a)$$

$$Investment\ LCOE = \frac{(Investment\ Cost) * T_C * FCR + AOE}{Annual\ Energy\ Production\ (net)} \quad (2b)$$

The total investment cost was modeled similarly based on the Dicorato model and the LCOE of investment was modeled to be like the Tegan NREL report, thus allowing for comparable results [21]. Of note, the view damage LCOE and aggregate LCOE calculations in the subsequent result sections do not have standard industry definitions for their LCOE. However in this study, they are still defined as LCOE for consistency in the aggregate calculations which is the summation of investment LCOE and societal view damage LCOE. This allows for comparisons to all other types of electricity generation.

2.2. View damage cost modeling

The view damage cost in this model is defined as the cost to residents from the visual disamenity of an OWF within the viewshed of a household. This is quantified by applying an existing contingent valuation willingness to pay (WTP) study, conducted in several Lake Michigan communities, based on how much a resident is willing to pay or willing to accept (WTA) as an additional cost or discount to their monthly electricity bill for a potential OWF located at a specific distance from shore [22]. The WTP/WTA cost values were collected from residents of Oceana and Mason County.

This paper applies the environmental benefit transfer methodology to extrapolate results from two coastal counties in Michigan to the entire Lake Michigan viewshed region [23]. While offshore viewshed preferences may differ strongly depending on regions, no other data exists on WTP/WTA to quantify cost values of residents in the other Michigan shoreline counties, so the Mason and Oceana County survey data was extrapolated across the whole shoreline. The WTP study utilized simulated OWF images at 3, 6, and 10 miles offshore and gathered survey data specific to those distances. This study extrapolates the WTP costs with a logarithmic trend to cover the spatial extent of the model. This is shown in Table 1 and Fig. 3 [22]. This extrapolation method is compared to a linear extrapolation as a sensitivity to this view damage cost model.

Table 1: Michigan mean WTP data based on Oceana and Mason County (Knapp [22])

Distances (miles)	[km]	WTP (\$/month)
3	4.8	-60.27
6	9.7	-43.07
10	16.1	-27.01

[insert Fig 3 here]

Fig. 3: Logarithmic extrapolation of Lake Michigan WTP data¹

The WTP of one household was determined based on the extrapolation (Fig. 3) and is a function of the OWF distance to shore ($D_{farmtoshore}$) as seen in Eq. 3a. These WTP results are primarily negative because they represent an external cost to individual households due to OWFs representing a visual disamenity. In Fig. 3 at 27.5 miles, when the costs become positive, individuals are willing to pay for the OWF and the view damage cost become benefits that can offset investment cost. The annual view damage cost (VDC) values were determined by WTA (negative of WTP) values applied to the total number of households (h) within the viewshed of the potential siting location for 12 months (Eq. 3b). With consideration for present-value, the total VDC was discounted at a rate of 3% over the 20 year (near future as defined by Weitzman) lifespan of the farm (Eq. 3c) [24]. This discount rate uses the gamma distribution (and exponential discounting) on probability averaged data from the expert opinion among academic economists to determine the global warming discount rate. This discount rate (r) is considered the social discount rate which is different from the previous private, financing discount rate used in the investment cost model (also defined as r), but holds the same value (3%). The discount rate is also reassessed at 5% and 7% in the view damage cost sensitivity analysis. Not shown in the equations, the WTP survey cost values were taken as USD 2013 and inflated to USD 2014 (\$1 in 2013 becomes \$1.02 in 2014) [20]. With the scope of the analysis confined to the state of Michigan, the total view damage cost only includes Michigan households and does not take into consideration the OWF viewshed impact of bordering states' households.

$$WTP \left[\frac{\$}{\text{month} \cdot \text{household}} \right] = 27.464 * \ln(D_{farmtoshore}) - 90.991 = -WTA \quad (3a)$$

$$\text{Annual VDC} \left[\frac{\$}{\text{year}} \right] = WTA * 12 \text{ months} * (h) \quad (3b)$$

$$\text{Net Present Value VDC} [\$] = \frac{\text{Annual VDC}}{r} * \left(1 - \frac{1}{(1+r)^n} \right) \quad (3c)$$

$$\text{View Damage LCOE} \left[\frac{\$}{MWh} \right] = \frac{\text{Net Present Value VDC}}{\text{Annual Energy Production (net)} * n} \quad (3d)$$

To determine the households within the viewshed of a siting location, the land elevation and topographical data were combined with the household count data [12] and integrated into the USGS Dasymetric Mapping tool to determine household density/distribution [25] [26]. From this, the household count was quantified and extracted (Fig. 4). Each OWF location was analyzed individually and interpolated with the Kriging function. The wind farm view point was modeled at the height of the farm

¹ The original study did not assume negative viewshed impacts and used both positive and negative WTP values (-\$60 to \$60) in the survey. While some participants do not express negative viewshed effects and have positive WTP values for the OWF, after aggregating the results the study concluded overall negative view results. In this study, the extrapolation across the negative WTP into positive WTP allows and includes potential distances where residents are willing to pay for the disrupted viewshed due to the value of clean energy exceeding the diminished viewshed impact.

(hub height combined with blade radius) and the affected land area was constrained by land elevation and earth curvature. This estimate for number of households is expected to be an overestimate due to the lack of data to incorporate tree or building obstructions in the viewshed.

[insert Fig 4 here]

Fig. 4: Example viewshed from one potential OWF location about 8.5 miles (13.75 km) away from shore

For context, the WTP cost model is compared to previous WTP studies that also apply nonmarket stated preference valuation methods to OWF siting. Three studies with WTP/WTa valuation results are completed for Delaware (Krueger [6]), Denmark (Ladenburg [27]), and East Carolina (Landry [28]). Krueger's Delaware study has a maximum WTa of about \$80/household/year at 0.9 miles from shore, while his comparison with Ladenburg's Denmark study has a maximum WTa result of \$160/household/year at 5 miles from shore [6] [27]. This current view damage cost model's maximum WTa data (Table 1) at 3 miles from shore is \$60/household/month, equating to \$720/household/year, which is substantially higher than the previous studies. Even at 5 miles, this view damage cost model would have the WTa of \$562/household/year, which is significantly higher than other studies. These WTa values are then shown to depend on the state/country. For this Lake Michigan location, the viewshed impacts are greater than previous studies. While the trends can be found to be similar among these OWF visual disamenity studies (lower values as OWF gets further from shore [29]), the actual WTP/WTa values can differ substantially [30]. There are also strong variations among the preferences as these other valuations also show positive WTP valuations similar to the WTP used in this study. The socio-demographic characteristics also vary spatially and temporally, across wide ranges, which further demonstrates the importance of using the representative WTP/WTa valuation scenarios, as in our study.

A second comparative perspective comes from an ex-post study of an onshore wind farm. The study shows that the farm exerted a negative effect on residential property values in the vicinity of the farm [31], where losses occurred in two out of three counties studied. This real impact in property values demonstrates the economic losses that may occur from wind turbines, losses that are external to the power generation itself.

2.3. Wind power generation modeling

The wind power generation modeling was based on Tsai's methodology for accounting for wind speed variability with the Weibull distribution [32]. This required taking the average wind speeds in the Great Lakes from NREL Wind Speed maps, extrapolating from the 90m given wind speed height to the 100m hub height using the Hellman exponent of 0.2, and applying the Weibull distribution (shape parameter $k = 2$) to estimate the various wind speeds throughout the year based on the mean annual wind speed [13]. The Weibull distribution estimation was used to calculate power generation at various wind speeds due to typical wind generation underestimates from assuming constant annual wind speeds [14]. The base scenario method from Tsai's model uses the assumed constant shape parameter ($k = 2$) and the

more accurate model varies the shape parameter ($k = 1.73 - 1.82$) to match the specific location's wind resource [32]. The base case resulted in a slight overestimate of 5 – 6% wind power generation over the more accurate model, but not enough location specific data was available to replicate the accurate wind speed model as demonstrated in Tsai's model [32]. The calculation for the wind power generation used a 1 m/s interval size for the wind speed frequency distribution and is based on the power curve of the Vestas V112, which ranged from 3 m/s to 25 m/s [15]. This approximation for the wind power generation is the electricity generated on site and includes 18% losses (10 – 20% losses from wake and up to 3% losses from transmission) and 98% availability [33] [34]. This comes from high uncertainty in wake loss modeling for large offshore wind applications. The wake effects are determined to be 12% and the wind turbine layout is found to be justified in comparison to similar existing OWF projects (Horns Rev I) [35]. As another study determined, the wake losses can be reduced by 1.3% per 1 rotor diameter increase [36], but this would increase the investment cost (higher O&M costs) and also increase the viewshed effect (larger OWF footprint) [35]. Overall, wake losses are found to range widely with a strong dependence on wind speed angle or turbulence effects [16]. So while these losses would typically vary with location and wind farm layout, in this case they were assumed to be constant in all regions. The result of this model is the Annual Energy Production (net) to be used for LCOE calculations.

3. Results

3.1. Investment cost

The investment cost results are shown in Fig. 5 where the categorizations of the costs in the figure are defined to highlight the differences by location rather than divided into equal intervals. These costs range from \$936 million (\$3,120/kW) to \$2,405 million (\$8,017/kW) for our 300 MW farm with an average cost of about \$1,470 million (\$4,900/kW). This investment cost is shown to be strongly correlated with the bathymetry factor (d) also portrayed in the model. Costs correlate more with bathymetry (d) than with distance from shore ($D_{bathdist}$). This can be predicted given the greater dependency d rather than the $D_{bathdist}$ from the investment cost equation (Eq. 1). This is due to the large investment cost coming from foundation cost (depth dependent) rather than installation cost (distance dependent), so the depth factor is more significant. The wind turbine cost is also a major aspect of the investment cost, but it does not depend on depth or distance. The transmission cost, which depends on both distance and depth, is a small portion of the total investment cost.

The investment cost is comparable with the current average market values. The range of reported average capital costs for OWF projects specified by Navigant's 2014 offshore wind economic analysis is \$5,187/kW for 2013 or \$5,385/kW for 2012 [2]. For our 300 MW farm, this would result in \$1,556 million, which is within the model's investment cost range and slightly over the average cost.

[insert Fig 5 here]

Fig. 5: Investment cost of 100 3MW Vestas V112 turbines in Lake Michigan priced in 2014 \$mill USD; the cost is a function of bathymetry (shown) and distance from shore

3.2. View damage cost

The view damage cost results are shown in Fig. 6 with a close-up view showing details in the highest cost region. Again the categorizations are in unequal intervals, and it should be noted that most of the Lake has very small costs. The lowest view damage cost are at locations farthest away from large near-shore population densities. The highest view damage cost are close to the shoreline where there are large viewsheds and dense populations (such as Muskegon and Ottawa County). The view damage cost range between -\$22 – \$2,209 million (-\$73/kW – \$7,363/kW) with an average cost of \$114 million (\$380/kW). A sensitivity analysis was also conducted using variations in both the discount rate and the extrapolation trend on the cost valuation result.

[insert Fig 6 here]

Fig. 6: Present-value view damage cost of 100 3MW Vestas V112 turbines in Lake Michigan based on Lake Michigan's WTP data extrapolated logarithmically, discounted by 3%, and priced in 2014 \$mill USD

3.3. Wind power electricity generation

The wind power generation was modeled for Lake Michigan and is shown in Fig. 7. The range of power generation in the entire Great Lakes region is 708 – 984 GWh annually (27% to 37.4% capacity factor) with an average of 910 GWh/yr (34.7% capacity factor).

[insert Fig 7 here]

Fig. 7: Annual wind power generation of 100 3MW Vestas V112 turbines in Lake Michigan

3.4. Aggregate cost

The investment cost spatial model and view damage cost spatial model were summed into a present-value aggregate cost as defined in Eq. 4 and shown in Fig. 8. The aggregate cost average is \$1,585 million (\$5,283/kW), ranging from \$1,005 to \$3,277 million (\$3,350/kW – \$10,923/kW). The investment cost is highest at the deep bathymetry locations and the view damage cost is highest at the large density locations. For the lowest cost, since the view damage cost is negligible in most of the lake, the minimum aggregate cost location is close to the minimum investment cost location. However, in the analysis of the highest costs, the aggregate cost follows the view damage cost trend by having the maximum cost at the large household density locations.

$$\text{Aggregate Cost} = \text{Investment Cost} + \text{View Damage Cost} \quad (4)$$

[insert Fig 8 here]

Fig. 8: Present-value cost comparison between (a) investment, (b) view damage, and their (c) aggregate (sum) for a 300MW OWF in Lake Michigan (in \$million) categorized in six equal intervals of \$550 million

The minimum aggregate cost is shown in Fig. 9 for each segment of the lake defined by extending the boundaries of Michigan shoreline counties. The minimum cost locations are rectangles drawn to scale of the 10x10 wind turbine farm layouts with spacing of 7 blade diameters in length and 4 diameters in width [14]. The lowest costs in the entire lake region are in the northern region of the lake correlating with shallow bathymetry, close distance to shore, and low household density. Farther south in the lake, the distance to shore and bathymetry factors are not as significant due to the overwhelming effect of high household density leading to higher overall costs. However these minimized cost locations are unrealistic to current OWF developers. The bathymetry can be as deep as 85 meters and as far as 60km from shore.

[insert Fig 9 here]

Fig. 9: Minimum aggregate cost by county-extended regions classified into low (\$1,005 – \$1,125), medium (\$1,126 – \$1,275), and high (\$1,276 – \$1,484) costs

To further quantify the total effect of the view damage cost compared to investment cost on the aggregate cost, Fig. 10a shows the fraction contribution from view damage cost as a maximum of 67% and an average of 7%. The aggregate cost throughout the lake has only a small region (bordering Ottawa County) where the view damage cost is over 50% while everywhere else is mainly influenced by the investment cost. The results show that the effect of high household density along with OWF in proximity to the shoreline is a dominant factor in the aggregate cost of OWF siting. However, since this view damage cost is very concentrated, the effect becomes less important in the majority of Lake Michigan. Additionally, the sensitivity analysis considers the variation of the view damage cost contribution as the parameters in the view damage cost model change.

[insert Fig 10 here]

Fig. 10: a) view damage cost share of aggregate cost b) view damage LCOE share of aggregate LCOE

3.5. Levelized cost of electricity (LCOE)

The wind power generation model was integrated with costs to create a levelized cost of energy (LCOE) comparison (\$/MWh). As mentioned previously, the investment LCOE is standardized, but the view damage LCOE is simply defined here as the societal view damage cost/benefit of the power generation resources. This results in a new definition for aggregate LCOE, which is the addition of the societal view damage LCOE plus the existing investment LCOE. The investment LCOE Eq. 2b was summed with the view damage LCOE Eq. 3d to create the aggregate LCOE summarized in Table 2 and shown in Fig. 11. The investment LCOE values are comparable to industry values such as \$225/MWh in the “2011 Cost of Wind Energy Review” by NREL [21].

Table 2: Summary of levelized cost of energy (LCOE) for the investment, view, and aggregate results ($n = 12.7 * 10^6$)

LCOE Model	Mean Cost [\$/MWh]	Std Dev.	Min Cost [\$/MWh]	Max Cost [\$/MWh]
Investment	249	37.7	180	367
View Damage	9	17.1	-2	169
Aggregate	256	35.7	183	368

[insert Fig 11 here]

Fig. 11: Cost comparison of (a) investment LCOE, (b) view damage LCOE, and their (c) aggregate LCOE for a 300MW OWF in Lake Michigan (in \$/MWh) categorized in six equal intervals of \$62/MWh

In Fig. 10b, the view damage LCOE contribution to aggregate LCOE has a maximum percentage of 46%, i.e., it never is a majority share. The average view damage LCOE contribution to aggregate LCOE (3%) is also much lower than the previous view damage cost contribution to aggregate cost (7%) in the cost scenario. The locations of the view damage impact trends are spatially the same, but there is a decrease of the view damage contribution when levelizing the costs with power generation. As OWF distance from shore increases, the investment cost increases significantly while wind power generation only increases slightly, so investment LCOE becomes much more significant than view damage LCOE. It is still seen that at locations farther from shore, the investment cost is the main factor and at locations near dense populations, the view damage cost is the main factor.

The wind power generation increases farther from shore similar to the investment cost and opposite to the view damage cost. With changes in wind power generation larger than the increase in investment cost, there would be a constant investment LCOE across the lake and large decreases in view damage LCOE across the lake. This would increase the impact of view damage LCOE on the aggregate LCOE. However, Fig. 10 shows how the change in energy production is minimal and would actually decrease the impact of view damage LCOE on the aggregate LCOE.

The ideal siting locations for OWFs in the Lake Michigan region were determined to be mainly influenced by investment cost/LCOE, which has a large effect from bathymetry. Therefore, ideal locations would be close to the Michigan shoreline (in general, shallower lake depths) and away from the large household density (such as Ottawa County).

4. View Damage Cost Sensitivity Analysis

Seeing that the view damage cost can be a significant impact, the sensitivity of it can be assessed by varying the discount rate, WTP data extrapolation trends, view damage effect categorization, and WTP data in the view damage cost model. If the discount rate is increased from 3% to 5% or 7%, the view damage cost contributes less to the aggregate cost. As is well known, higher discount rates lower present-value costs for a given set of future values (Table 3). The original cost is represented as the base case (3% discount rate with logarithmic extrapolation) and can be seen as higher than the other cases. The view damage cost model's spatial trends based on the varying discount rates can also be seen in Fig. 12 (Appendix C). In this sensitivity, due to lower view damage cost, the investment cost would

contribute a larger share to the aggregate cost and is more influential in the determination of the siting location.

Table 3: Sensitivity of discount rates and extrapolation trends of view damage cost

Extrapolation Trend	Discount Rate	Mean Cost [\$mill]	Std Dev.	Min Cost [\$mill]	Max Cost [\$mill]
Logarithmic	3% (base case)	\$114	226.6	-\$22	\$2209
	5%	\$96	189.9	-\$18	\$1850
	7%	\$81	161.4	-\$16	\$1579
Linear	3%	\$86	210.5	-\$109	\$1733

Changing the extrapolation function from logarithmic to linear would be more influential than changing the discount rate by having a much lower minimum cost (-\$109 million). The new trend would also lead to a stronger correlation (larger R value by 0.0002), but this effect is disregarded due to only having three data points (see Fig. 13 Appendix C). In Table 3, the linear extrapolation view damage cost is not as significant as the logarithmic view damage cost analyzed in this study (mean cost of \$86 million and \$114 million respectively). The new view damage cost contributes less to aggregate cost due to smaller OWF distance to shore before the WTA values become WTP values (assuming the same 3% discount rate). However, this linear extrapolation trend is less likely to be a factor because previous WTP studies show a logarithmic trend rather than linear for WTP over farther distances [6] [27]. The view damage cost model's spatial trends based on the varying extrapolation trends can be seen in Fig. 14 (Appendix C).

Another factor to change in the view damage cost model is the classification of view effects. The current view damage cost is based on the total viewshed as determined spatially in ArcGIS. This overestimates the amount of homes that can physically perceive the potential OWF and underestimates the number of local homes that may have a cost based on proximity rather than viewshed. This view effect can instead be categorized as (a) the total amount of homes within a certain distance to the potential OWF or (b) the total amount of homes within the county (or city/town) boundaries associated with the lake region occupied by the OWF. In either scenario, increasing the affected view area would lead to a larger view damage cost, but decreasing the affected view area (e.g. to only 20 km radius to the OWF) would have a smaller view damage cost. Finally, the current WTP study utilizes data taken from entire counties (Mason and Oceana), which means that residents outside the viewshed region might have been surveyed. Therefore, the WTP for only the households within the viewshed (such as closer proximity to shoreline or higher elevation) may be higher (since these households would literally have a view of the lake). If this is the case, the current WTP data would underestimate the view damage cost. These are the factors that can lead to increases of the view damage in this study.

5. Conclusions

By analyzing both the investment cost and view damage cost, a framework is developed to assess spatial tradeoffs in OWF locations in Lake Michigan and to identify a least cost siting location. The location of the prospective wind farm was influenced by factors such as bathymetry, distance to shore, and household density. These factors determined the values and relative shares of the investment cost/LCOE

and view damage cost/LCOE in the aggregated cost/LCOE. The main factor influencing investment cost is bathymetry, which is slightly correlated to distance to shore and thus resulted in minimized locations close to the shoreline. The main factor influencing view damage cost is household density, so the least cost locations were in the northern part of the lake (far from large population centers). After aggregating these costs, the view damage cost is negligible in most of the Lake, but significant along the coast of Muskegon County and Ottawa County. After levelizing the costs with energy generation, the high investment LCOE contributes most to the aggregate LCOE and the view damage LCOE never exceeds a 50% share. These models, shown as maps, can serve as a visual guide to inform stakeholders to understand quantitative tradeoffs that may facilitate OWF siting in the Great Lakes region.

While this study analyzed Michigan's offshore wind potential in Lake Michigan, this approach can be applied to other locations. The only major challenge is the availability and relevance of the visual disamenity WTP model. As discussed before, the analysis of WTP values not only encompass a large range between favorable and unfavorable values, but also changes drastically with respect to time and space. By applying appropriate valuation methods and benefit transfer methods, this type of study can be done in other regions and can help guide OWF siting throughout the world.

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Appendix A:

Multi-criteria analysis modules (and their dominant factors: distance or depth)

[insert Mod1 here]

[insert Mod2 here]

[insert Mod3 here]

Appendix B:

Investment cost calculations:

Cost [k\$]	Equation		Factors
Wind Turbine	$C_{WT} = 1.1 * n_{WT} * 2.95 * 10^3 \ln(P_{WT}) - 375.2$	n_{WT} = # wind turbines P_{WT} = rated power [MW]	Fixed
Foundation	$C_f = 1.5 * n_{WT} * 320 P_{WT} (1 + 0.02(d - 8))(1 + 0.8 * 10^{-6}(h(r)^2 - 10^5))$	d = depth [m] h = hub height [m] r = radius of blade swept area [m]	$f(d)$
Collection System	$C_{CS} = (C_{C;MV} + C_{i;MV}) * D_{CS}$ $C_{C;MV} = 0.4818 * S + 99.153$ $C_{i;MV} = 463$ $D_{CS} = (100 * (d + 1) + 10 * 7156 + 6260) / 1000$	$C_{C;MV}$ = cable transport and installation cost [k€/km] $C_{i;MV}$ = submarine cables cost [k€/km] S = cable section [mm ²] D_{CS} = total cable length (function of depth) [km]	$f(d)$
Transmission	$C_{TS} = 1.946 * D_{bathdist} + (2.24 * D_{shoretoTS})$	$D_{bathdist}$ = least cost path distance from OWF to shoreline [km]	$f(D_{bathdist})$
Integration System	$C_{IS} = 2 * 21656$	(These values are the same as Dicoratos' model where the base case was doubled to account for the larger farm size)	Fixed
Grid Interface	$C_{GI} = 2 * 3750$		Fixed
Development	$C_D = 7020$	(This value is the same as Dicoratos')	Fixed
Total	Investment Cost = 815 + (4.842 * d) + (1.946 * $D_{bathdist}$) + (2.24 * $D_{shoretoTS}$)	Where $n_{WT} = 100$, $P_{WT} = 3$ MW, $h = 110$ m, $r = 56$ m, $S = 630$ mm²	$f(d, D_{bathdist})$

Appendix C:

View damage cost sensitivities:

[insert Fig 12 here]

Fig. 12: View damage cost comparison between (a) 3% discount rate, (b) 5% discount rate, and (c) 7% discount rate for a 300MW OWF in Lake Michigan (in 2014\$mill)

[insert Fig 13 here]

Fig. 13: Linear extrapolation of Lake Michigan WTP data

[insert Fig 14 here]

Fig. 14: View damage cost comparison between (a) logarithmic extrapolation and (b) linear extrapolation for a 300MW OWF in Lake Michigan (in 2014\$mill)

EXHIBIT 1

Wind Resource Areas, June 2010

SOURCE: Institute for Fisheries Research, UMMDNRE, 2010.

EXHIBIT 3

Application of Mapping Criteria as of October 2010

SOURCE: IFR October 2010.

NOTE: Data on underwater archaeological sites, buoyed navigation channels, and submerged transmission lines are not currently available and therefore are not reflected in the maps in this report. Data for some of the mapping criteria, such as commercial fishing, shipwrecks, and habitat, are incomplete.

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

(a) Logarithmic Extrapolation

(b) Linear Extrapolation

View Damage Cost [\$mill]

----- Michigan Lakes Border

0 20 40

Kilometers