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

by

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Abstract

Investment and view damage costs are important determinants in siting locations for 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. 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.

Acknowledgements

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This thesis would not have been possible without the many advisors and colleagues I have had the opportunity to work with. I would like to sincerely thank Professor Greg Keoleian for sharing his tremendous expertise and guiding me in conducting interdisciplinary research. I would also like to thank Prof. Michael Moore, Prof. Jeremiah Johnson, Prof. Dan Brown, and Dr. Jarod Kelly for their knowledge and support. I am forever grateful for my fellow colleagues in the Center for Sustainable Systems and the School of Natural Resources and Environment for their various ideas and assistance.

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Preface

There are many system-wide impacts that can be considered for a renewable or traditional energy generation project in selecting a project location, however currently the main focus is on analyzing and reducing the project costs. This interdisciplinary thesis explores the impacts from the investment cost and view damage cost to determine the ideal siting location of an offshore wind farm in Lake Michigan. Results here are presented quantitatively and spatially in evaluating the tradeoffs between these two impacts. This analysis can be used to inform policy decisions to include community viewshed preferences in the Lake Michigan region. This study has been submitted for publication.

Not included in this thesis is my current research focusing on emission abatement benefits analysis and system-wide siting optimization. The electricity grid emissions offset by an offshore wind farm is evaluated as an environmental benefit to order to determine the influence on siting location. Additionally, the system can be optimized with regards to the investment cost, view damage cost, and emission abatement benefits to further elucidate the tradeoffs. These current studies will also be submitted for publication.

Investment Cost and View Damage Cost of an OWF

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 (Global Wind Energy Council). Over 1.1 GW (2.4%) of the 45 GW increase was from offshore wind power (Hahn and Gilman). For the United States, 13 GW of wind power was added in 2012, none of which came from offshore wind power sources (Wiser and Bolinger).

The DOE (Department of Energy) has invested $227 million in offshore wind projects and research since 2011 (Wiser and Bolinger). 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) (Wiser and Bolinger). 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 (Klepinger, Planning for Offshore Wind Developments in Michigan's Great Lakes - Background Materials). In this case, the viewshed is not considered a separate cost, but rather a factor to be aware of. This thesis instead looks at the view damage cost as a separate tradeoff with just as much 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 (Klepinger, Report of the Michigan Great Lakes Wind Council). The results of this are presented in Fig. 1 shown below. 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 (Scandia Wind Offshore). 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 (Ferber). 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 (Scandia Wind Offshore). 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.

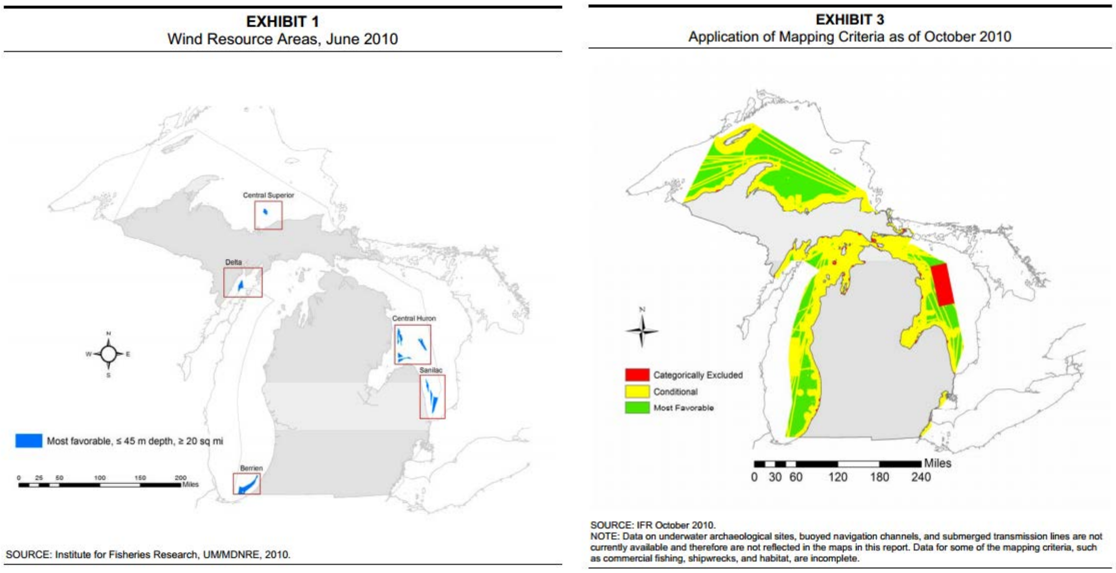
EXHIBIT 1
Wind Resource Areas, June 2010

SOURCE: Institute for Fisheries Research, UM/MDNRE, 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.

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 (Klepinger, Report of the Michigan Great Lakes Wind Council))

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 levelized 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) (Klepinger, Report of the Michigan Great Lakes Wind Council). 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 and 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 (Michigan Department of Technology, Management & Budget). 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 (National Historical Geographic Information System). Data on wind speeds are used with the power generation curves as the factors used to create the wind power generation model (Musial and Ram).

Each model analyzes the lake in the resolution of 30 meters x 30 meters which resulted in the number of unique locations to be around 12.6 million. The models also include assumptions (such as fixed parameters which are 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 (Vestas’ V112 rotor diameter is 110 meters) from west to east (Masters) (Vestas Wind Systems A/S). This layout is a standard placement to minimize wake effects (wind turbulence of one turbine affecting the wind reaching the turbine downwind of it) 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 (Calvin College). 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 (Dicorato, Forte and Pisani). 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, which can account for 20% - 30% of the total lifecycle cost (Musial and Ram). 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 (bathymetry distance to shore, $D_{bathdist}$; [km]) as seen in Fig. 2. This "$D_{bathdist}$" factor was calculated using ArcGIS based on the view distance between the farm to the Michigan shoreline ($D_{farmtoshore}$; [km]) and "d". These three factors are fundamentally dependent on the geographic location.

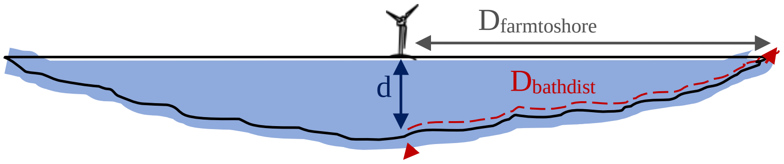

Fig. 2: Distance and depth factors in the investment cost model (not to scale)

Following the Dicorato model involved including a fixed exchange rate from euros to U.S. dollars which was €1:$1.4 based on the 2009 data in the Dicorato model (Dicorato, Forte and Pisani) (X-Rates). This cost is converted to 2014 dollars (2014$; $1 in 2009 becomes $1.11 in 2014) to account for inflation (U.S. Bureau of Labor Statistics). The investment cost model was simplified by the assumptions made in Dicorato, such as parallel AC connections between turbines for the transmission configuration (Dicorato, Forte and Pisani). This cost could then be calculated for the entire Lake Michigan region using the raster calculator tool in ArcGIS. The investment cost [$mill USD] can be expressed in Eq. 1 below as a function of the factors described above ($D_{bathdist}$ and d) 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 (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 will be included in the levelized cost of electricity (LCOE) model (Dicorato, Forte and Pisani).

For the LCOE of investment, additional costs were added to this 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 ($40.8 mill for the 300 MW farm) was applied at all locations for the land lease, O&M, and replacement parts cost (Tegan, Lantz and Hand). A fixed charge rate (FCR) was computed, using a 10% prime interest rate, to represent the annual cost of debt servicing for the upfront investment cost. This was based on the Tegan 2013 NREL report using a FCR of 11.7% as shown in Eq. 2a (Tegan, Lantz and Hand). The calculated net annual energy production [GWh/yr] is discussed in section 2.3. The final investment LCOE [$/MWh] is shown in Eq. 2b below.

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

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

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 (Tegan, Lantz and Hand).

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 (Knapp, Li and Ma). 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 (Freeman, Herriges and Kling). While offshore viewshed preferences may differ strongly depending on regions, no other data exists on WTP/WTA to quantify cost values of residents in other 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, and 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 (Knapp, Li and Ma).

Table 1: *Michigan mean WTP data based on Oceana and Mason County (Knapp (Knapp, Li and Ma))*

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

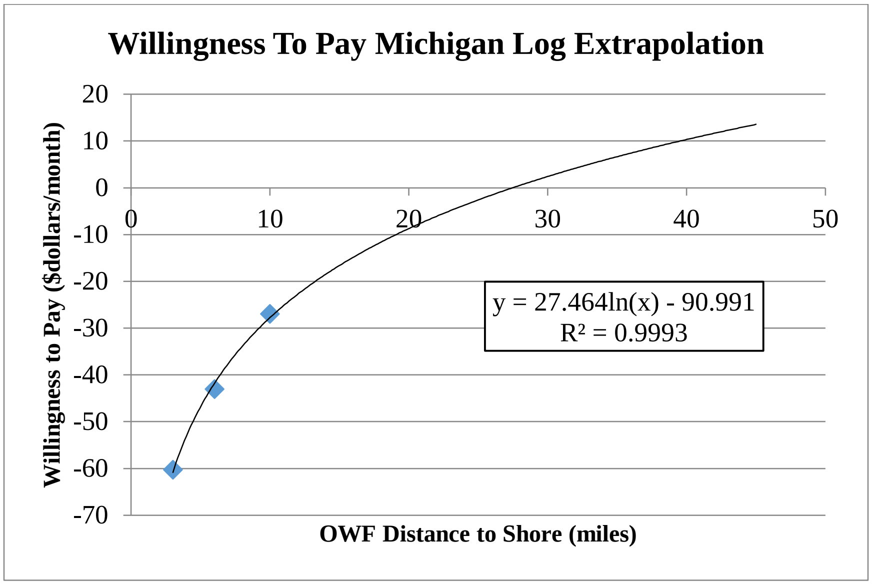

Fig. 3: Logarithmic extrapolation of Lake Michigan WTP data[1]

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[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

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 would 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) (Weitzman). This discount rate is considered the social discount rate which is different from the previous private, financing discount rate used in the investment cost model. Not shown in the equation, the WTP survey cost values were taken as USD 2013 and inflated to USD 2014 (inflation of 1:1.02) (U.S. Bureau of Labor Statistics). 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.

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

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

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

$$View\ Damage\ LCOE\ \left[\frac{\$}{MWh}\right] = \frac{Annual\ VDC}{Annual\ Energy\ Production\ (net)} \tag{3d}$$

To determine the households within the viewshed of a siting location, the land elevation and topographical data were combined with the household count data (National Historical Geographic Information System) and integrated into the USGS Dasymetric Mapping tool to determine household density/distribution (USGS) (Sleeter). The viewshed tool in ArcGIS was used to determine the dasymetric areas (household density characterized by land cover) that would see each OWF and the household count was quantified and extracted from this. An

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study, the extrapolation across the negative WTP into positive WTP allows and includes potential distances where residents are WTP for the disrupted viewshed due to the value of clean energy exceeding the diminished viewshed impact.

example of this can be seen in Fig. 4 below. Since individual locations were analyzed, the Kriging function was used to interpolate between calculated locations to model the entire Lake Michigan study area. The wind farm view point would be at the height of the farm (100m hub height, and 155m blade tip height) and the affected land area is 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.

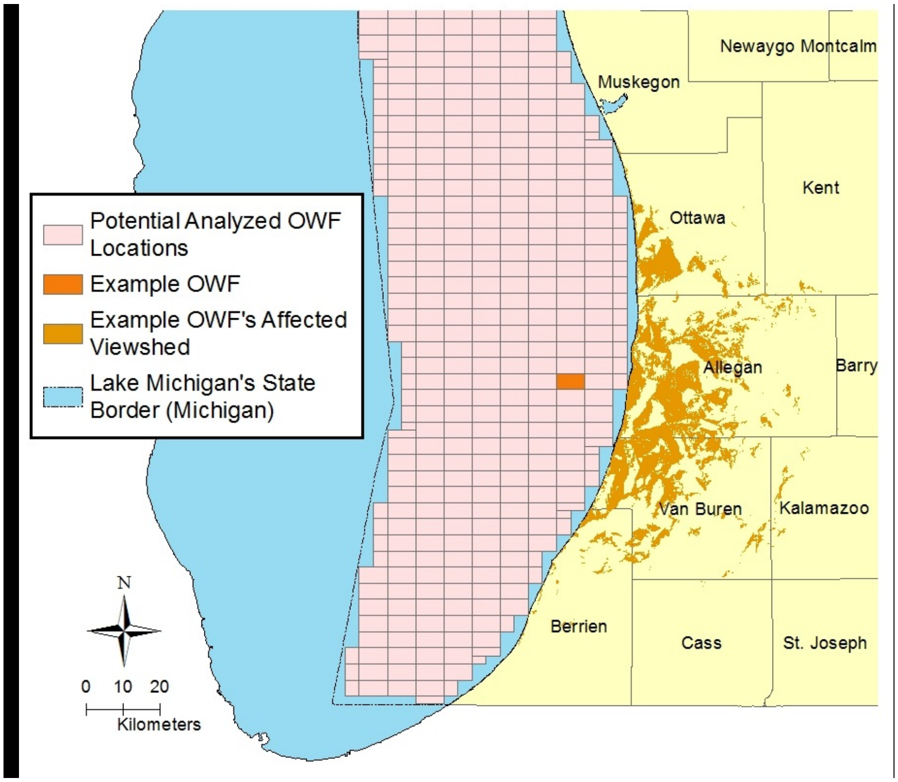

Fig. 4: Example viewshed from one potential OWF location about 8.5 miles (13.75 km) away from shore

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 (Tsai). This involved taking the average wind speeds in the Great Lakes from NREL Wind Speed maps (4.625 to 9.375 m/s in Lake Michigan), 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 (Musial and Ram). 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 (Masters). 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 (Tsai). The base case resulted in a slight overestimate of 5 – 6% wind power generation over the more accurate model that varied the shape parameter to meet specific location's wind resource, but not enough location specific data was available to create the accurate wind speed model as demonstrated in Tsai's model (Tsai). The calculation for the wind power generation from the wind speed frequency distribution is based on the power curve of the Vestas V112 (Vestas Wind Systems A/S). 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 (Barthelmie, Hansen and Frandsen) (Barberis Negra, Todorovic and Ackermann). These losses would typically vary from location and wind farm layout, but in this case they were assumed to be constant in all regions.

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 not divided into equal intervals, but defined to highlight the differences by location. 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}$). This can be predicted given the greater dependency on 'd' rather than the '$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 $5187/kW for 2013 or $5385/kW for 2012 (Hahn and Gilman). For our 300 MW farm, this would result in $1556 million, which is within the model's investment cost range and slightly over the average cost.

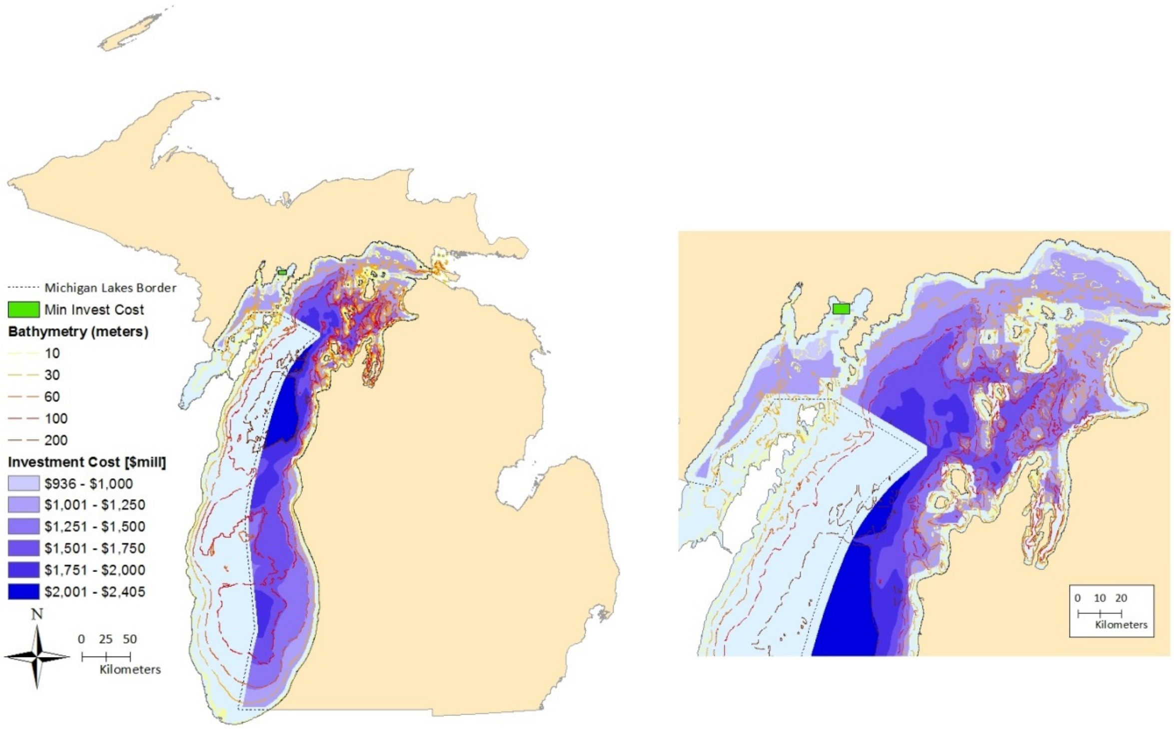

Fig. 5: Investment cost of 100 3MW Vestas V112 turbines in Lake Michigan priced in 2014 $mill USD; the cost is a function of bathymetry (shown) and distance from shore

3.2. View damage cost

The view damage cost results are shown in Fig. 6, below, 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).

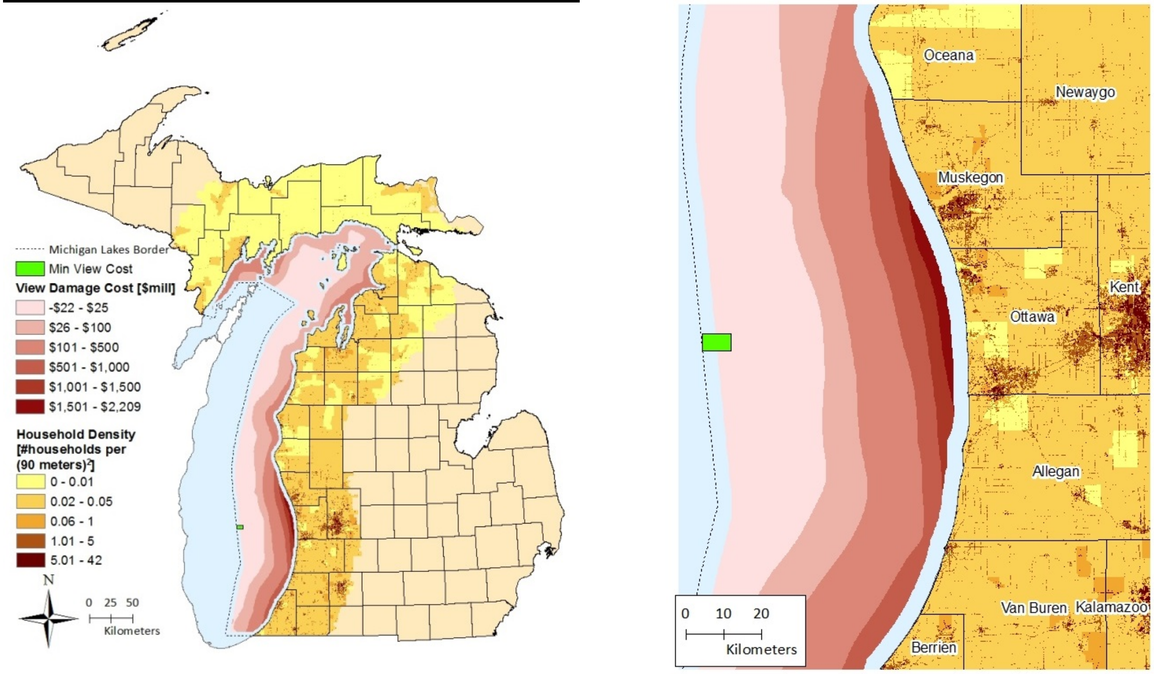

Fig. 6: Present-value view damage cost of 100 3MW Vestas V112 turbines in Lake Michigan based on Lake Michigan's WTP data extrapolated logarithmically and discounted by 3% and priced in 2014 USD

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).

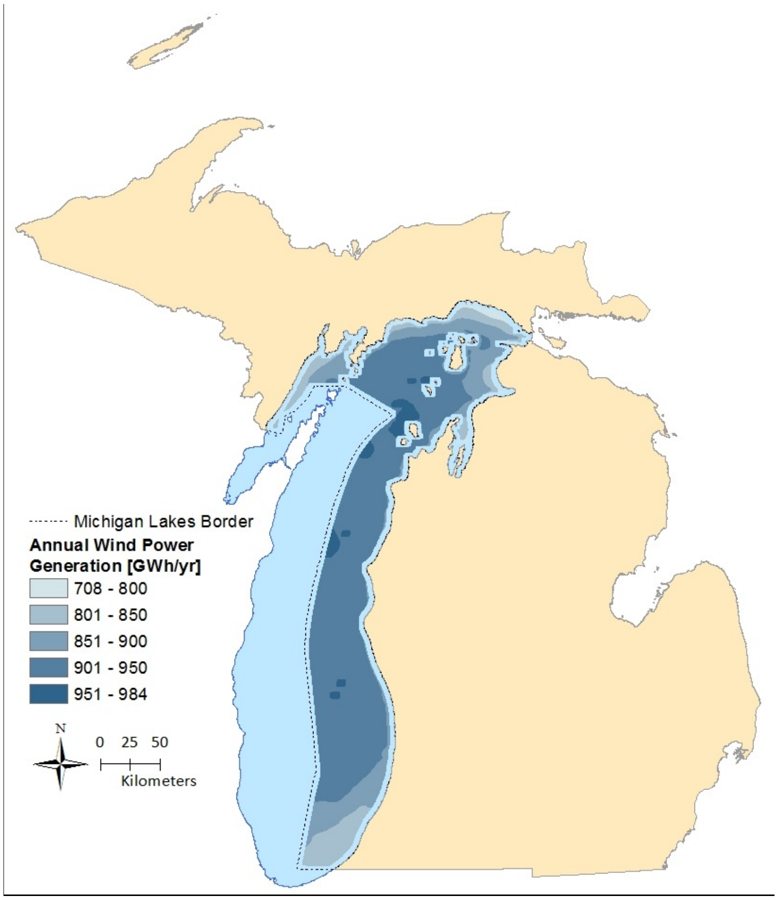

Fig. 7: Annual wind power generation of 100 3MW Vestas V112 turbines in Lake Michigan

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.

$$Aggregate\ Cost = Investment\ Cost + View\ Damage\ Cost \tag{4}$$

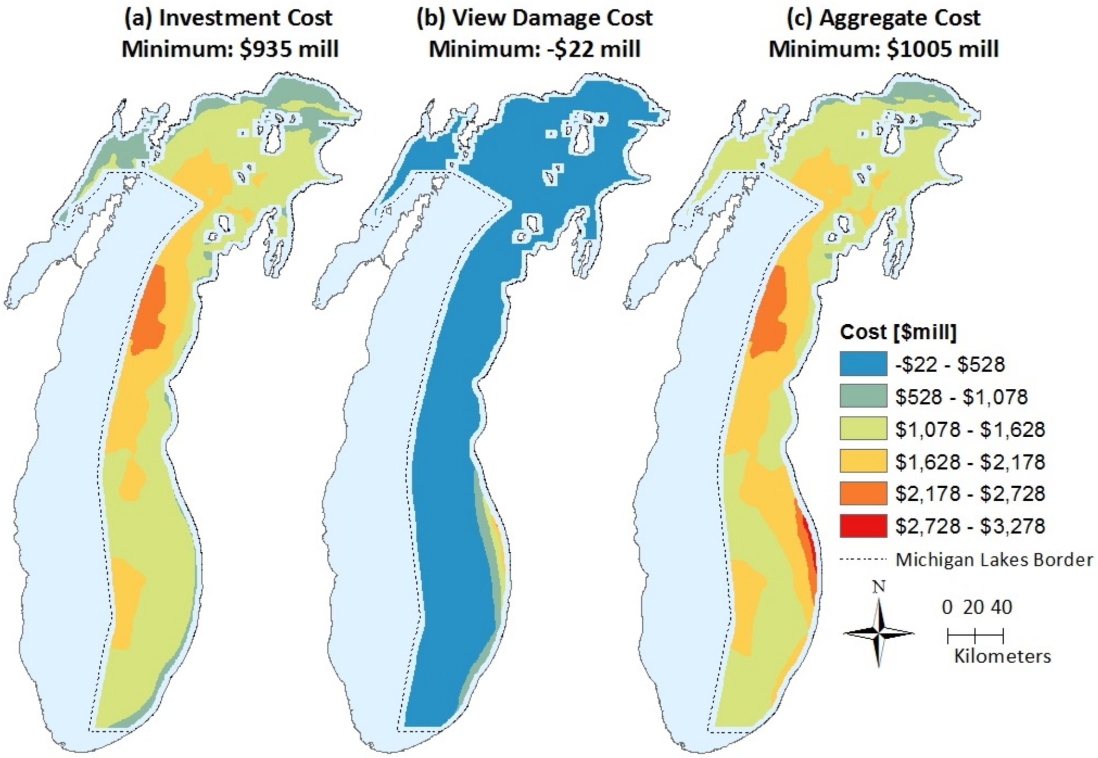

Fig. 8: Present-value cost comparison between (a) investment, (b) view damage, and their (c) aggregate (sum) for a 300MW OWF in Lake Michigan (in $million) categorized in six equal intervals of $550 million

The minimum aggregate cost is shown below 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 (Masters). 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 and minimized cost locations unrealistic to current OWF developers. The bathymetry can be as deep as 85 meters and as far as 60km from shore.

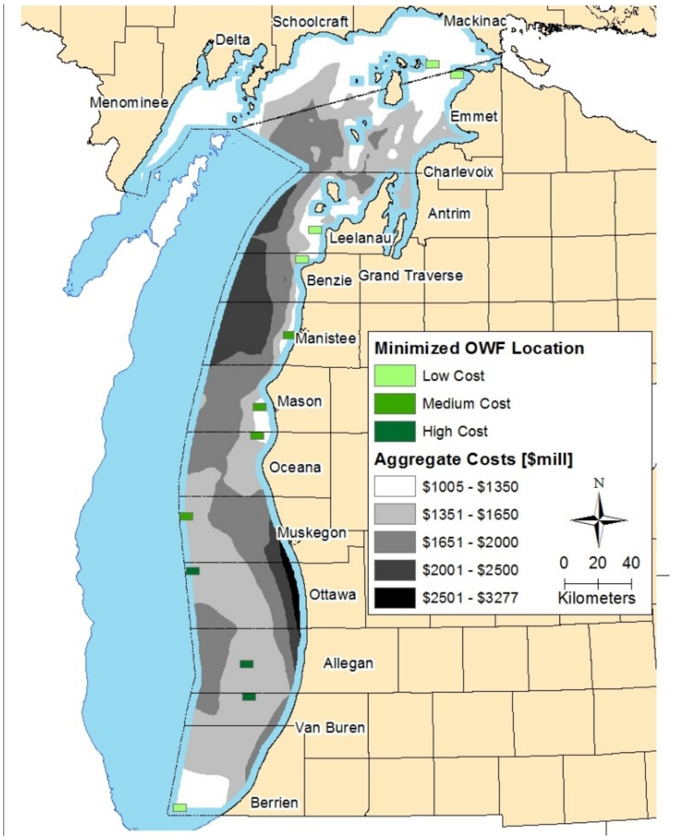

Fig. 9: Minimum aggregate cost by county-extended regions classified into low ($1005 – $1125), medium ($1126 – $1275), and high ($1276 – $1484) costs

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.

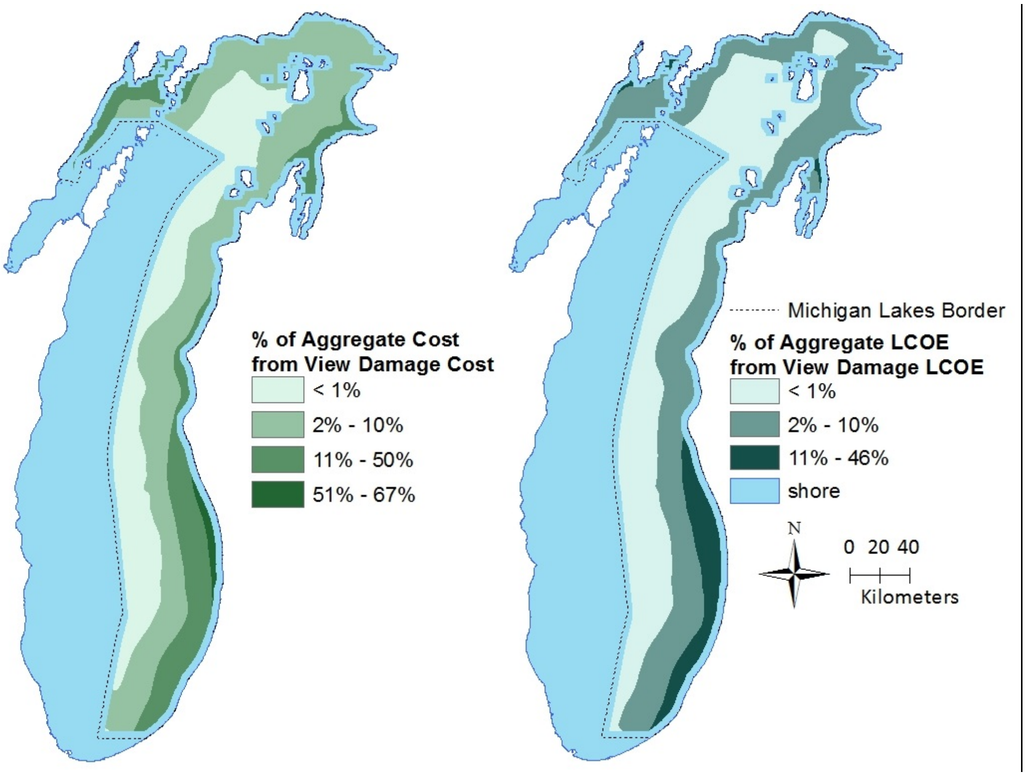

Fig. 10: a) view damage cost share of aggregate cost b) view damage LCOE share of aggregate LCOE

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). 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 (Tegan, Lantz and Hand).

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

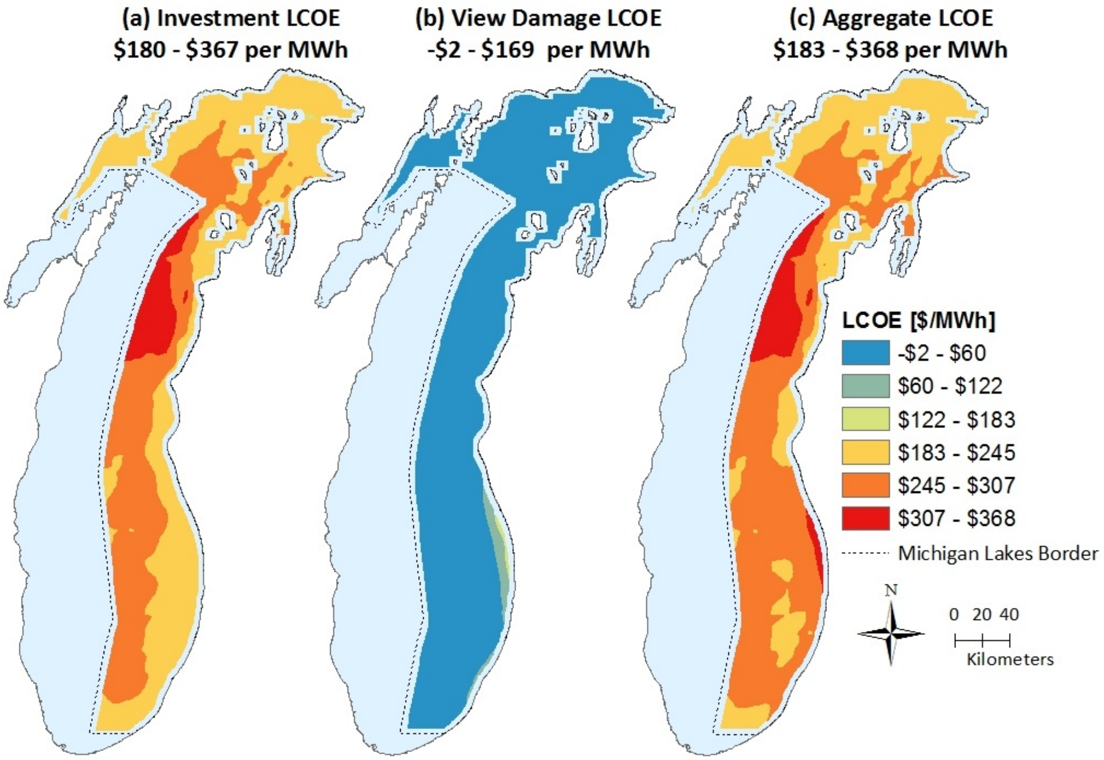

Fig. 11: Cost comparison of (a) investment LCOE, (b) view damage LCOE, and their (c) aggregate LCOE for a 300MW OWF in Lake Michigan (in $/MWh) categorized in six equal intervals of $62/MWh

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 cost/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 view damage cost model's spatial trends based on the varying discount rates can also be seen in Fig. 12 in Appendix C. Due to lower view damage cost, the investment cost contributes 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%*	**$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 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 [26] [27]. The view damage cost model's spatial trends based on the varying extrapolation trends can be seen in Fig. 14 in 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, which 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 (for example to only within 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.

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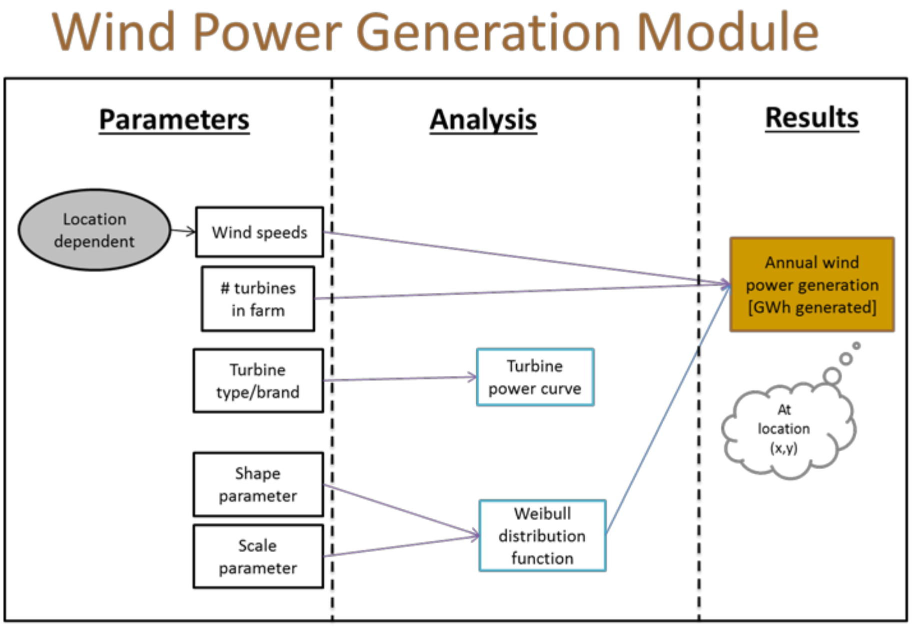
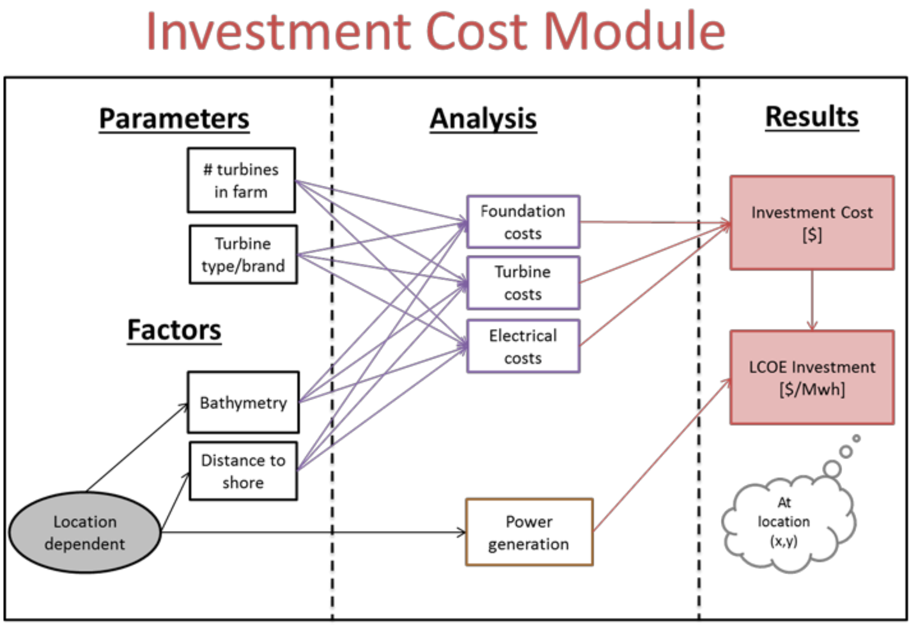
Appendixes

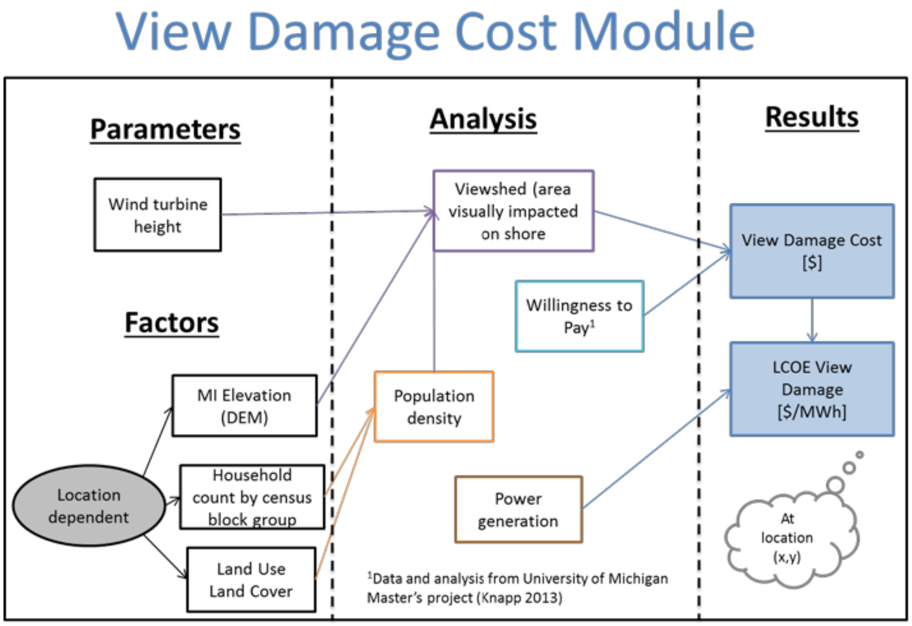
This section provides additional material on the analysis modules, investment cost calculations, and view damage sensitivities.

A

Multi-criteria analysis modules (and their dominant factors; such as distance and depth):


Wind Power Generation Module


Investment Cost Module



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] $C_{c;MV}$ = 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 mm^2**	**f(d, $D_{bathdist}$)**

C

View damage cost sensitivities:

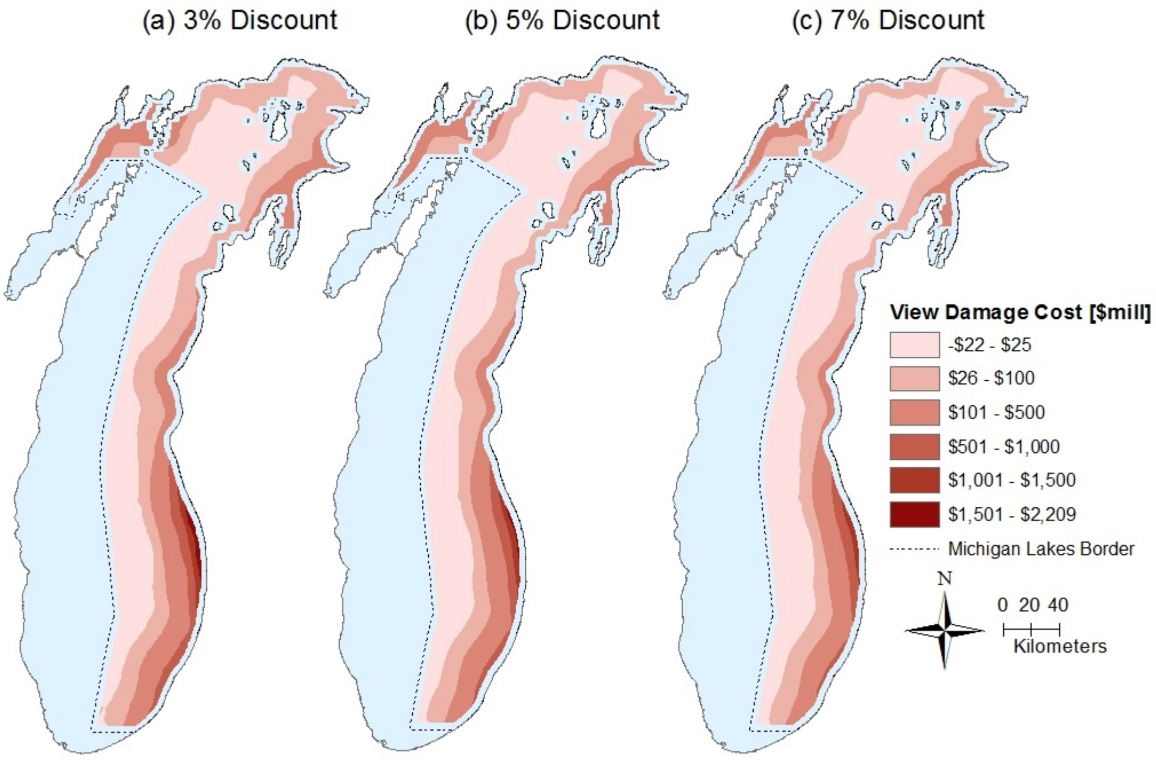


Fig. 12: View damage cost comparison between (a) 3% discount rate, (b) 5% discount rate, and (c) 7% discount rate for a 300MW OWF in Lake Michigan (in $million)

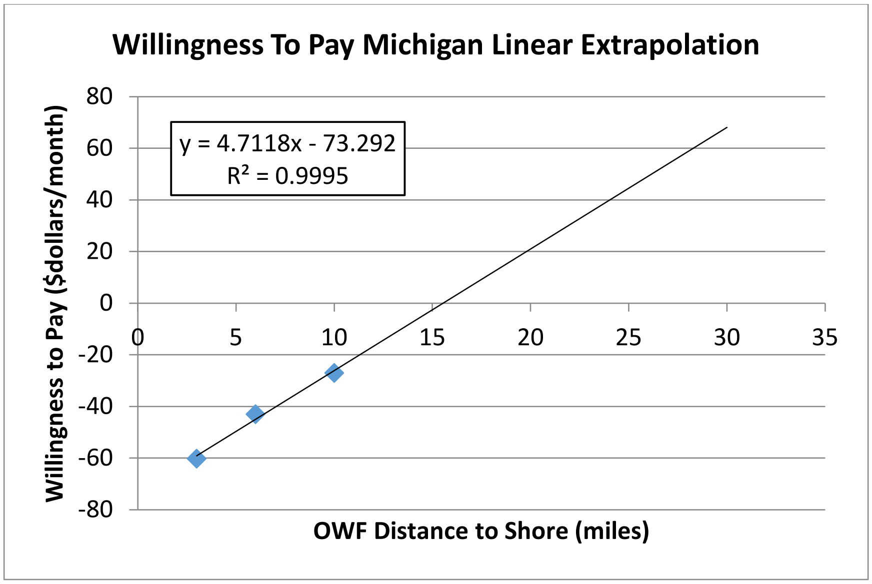


Fig. 13: Linear extrapolation of Lake Michigan WTP data

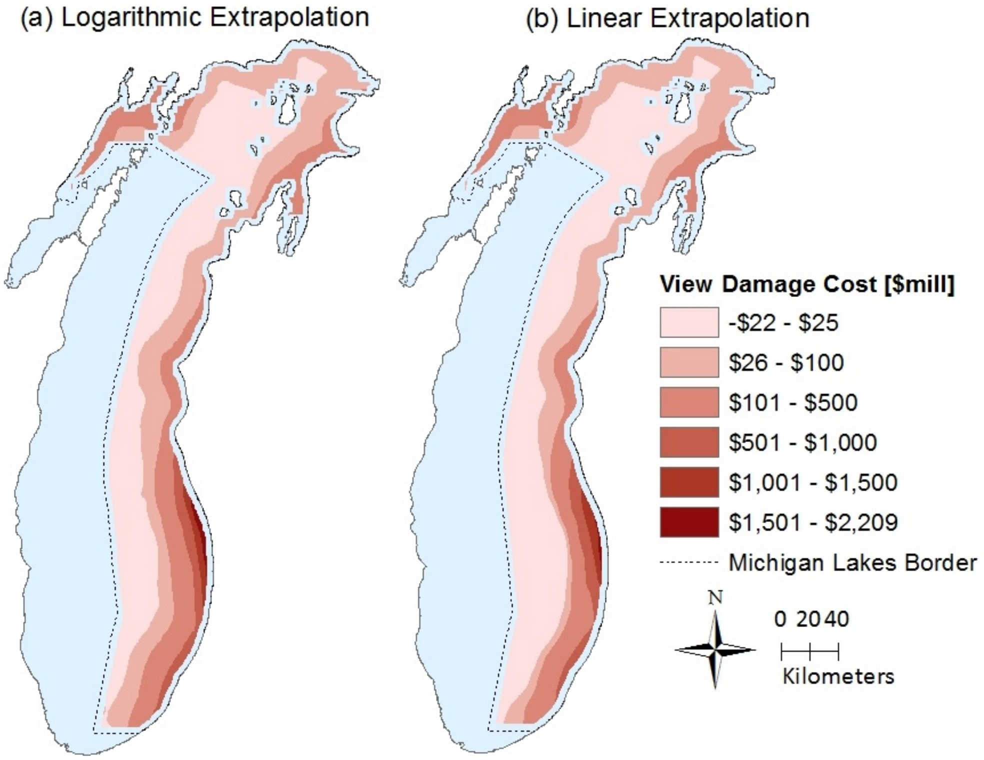


Fig. 14: View damage cost comparison between (a) logarithmic extrapolation and (b) linear extrapolation for a 300MW OWF in Lake Michigan (in $million)