An Integrated Assessment of Offshore Wind Farm Siting:
A Case Study in the Great Lakes of Michigan

By

Liang Tsai

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Doctoral Committee:

Professor Gregory A. Keoleian, Co-Chair
Professor Daniel G. Brown, Co-Chair
Professor Michael R. Moore
Professor Ian A. Hiskens
Assistant Research Scientist Jarod C. Kelly

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Abstract

Offshore wind farm (OWF) siting is crucial in determining the success of wind energy projects relative to multiple objectives, including increasing energy generation, decreasing installation costs, reducing life-cycle environmental impacts, displacing pollutant emissions, and reducing visual impact of wind turbines. This study examines the performance across these objectives for twenty siting scenarios in four Great Lakes counties and at various offshore distances. To evaluate wind energy potential of remote sites using wind-speed profiles, the shape parameter of the Weibull distribution of wind speeds at known weather stations was extrapolated using geostatistical kriging (Ch. 2). The best estimate of the shape parameters at candidate OWF locations varied from 1.73 to 1.82, indicating that the commonly used value of 2 may over-estimate the wind speed distribution at wind speeds that wind turbines can generate electricity.

Life-cycle environmental impacts of OWFs were evaluated using a process-based life cycle assessment for a 100 x 3MW OWF at twenty sites (Ch.3). The OWF manufacture, transportation, installation, use phase, and decommissioning contribute that, on average, one kWh of delivered electricity from OWFs will lead to global warming potential (GWP), acidification potential (AP), and cumulative energy demand (CED) impacts of 36 g CO_2eq, 0.012 mole H+eq, and 0.14 kWh fossil fuel, respectively. The environmental benefits for the same OWF scenarios are also evaluated by considering the displaced air pollutant emissions from using wind energy (Ch. 5). The monetized net benefit values for the avoided emissions ranges from $105 to $773 million, depending on the OWF locations and on the renewable energy and pollution policy mechanism.

Another OWF externality resulting from negative visual impacts was characterized and valued by combining viewshed simulation with estimates of willingness to pay data for moving wind turbines farther offshore (Ch. 4). The results show that the magnitude of visually impacted areas and population, and the monetized external cost of visual impact, decreased with increasing distance offshore and depended on the turbine dimensions, OWF locations, population density and distribution, coastline trend, and terrain.

Finally, an integrated assessment of OWF siting investigated the trade-offs between four objectives: energy, economy, environment, and society. The multiple criteria decision analysis with subjective weighting, objective weighting and monetization approaches are compared to illustrate different preferences and values toward OWF objectives (Ch. 6). The main findings are

1) the net monetized values of twenty siting scenarios with 300 MW wind turbines over a 20 year period are determined mainly by almost equally important objectives in energy benefits (averagely $1.2 billion) and installation cost (averagely -$1.2 billion), followed by net environmental benefits (between $0.1 billion to $0.7 billion), and lastly by external cost of visual impact (averagely -$4 million); 2) one of the weighting methods (weights energy, economic, environmental, and social objectives as 40%, 40%, 10% and 10%, respectively) is more representative than other six weighting methods and four monetization approaches because it has higher correlation with other weighting and monetization methods in performance rankings of siting scenarios; 3) small changes in the offshore distance of OWFs can cause significant differences in net benefit values; and 4) renewable energy certificates (RECs) are the most effective mechanism to increase environmental benefits and promote the development of OWFs considering the overall benefits to society.

The results of this study are expected to provide more diversified information of wind energy projects for stakeholders and decision makers. Meanwhile, the findings can inform wind-energy-related policy in order to maximize the benefits of OWFs to the society as a whole.

Chapter 1 Introduction

1-1 Wind energy in the United States

1-1-1. Wind energy benefits and development

Wind energy has the potential to make an important contribution to a clean, secure and diversified American energy mix. Utilizing this renewable energy resource presents potential benefits for mitigating global climate change, improving environmental quality and human health, providing national energy security and independence, and revitalizing the domestic manufacturing sector. According to an American Wind Energy Association (AWEA) report, by the end of 2012, there were more than 45,100 wind turbines installed across the United States (U.S.) [1]. The cumulative installed capacity reached a total of 60 GW, equivalent to the electricity generation of approximately 52 coal plants, or 320 million barrels of oil [1]. This avoided roughly 95.5 million tons of CO_2 emissions (4.2% of the CO_2 emissions of the entire power sector), lead to the annual conservation of 36.6 billion gallons of water, and represents an investment of $129 billion in the U.S. [1]. Although none of the current operational utility-scale wind farms are offshore in the U.S., thirteen projects have advanced significantly in the U.S. permitting process. As can be seen from Figure 1-1, offshore wind turbines are widely distributed in the waters of the forty-eight contiguous states of the U.S., except for Pacific coastal areas.

In addition to these benefits, offshore wind energy, compared to land-based wind energy, provides more stable and economically viable electricity generation, due to the steadier and faster wind speeds in coastal areas. According to estimations from the National Renewable Energy Laboratory (NREL), in U.S. waters, which include the Great Lakes, with a depth less than 60 meters and an annual average wind speed above 7 m/s, the total gross wind resources available are 4150 GW, which is equivalent to four times the generating capacity of the current

U.S. electric power system [2]. The state of Michigan has the potential to significantly increase its own wind generation capacity given its considerable offshore wind resources. This offshore generation potential is estimated to be about 55,250 MW in Michigan waters with a depth less than 30m [3], which is equivalent to 180% of the current state capacity. [4] Another advantage of offshore wind energy is that, unlike onshore wind energy, the generation corresponds to the periods of greatest electricity demand [5]. Further, the geographical proximity of offshore wind turbines to populous centers can reduce electricity losses due to long distance transmission.

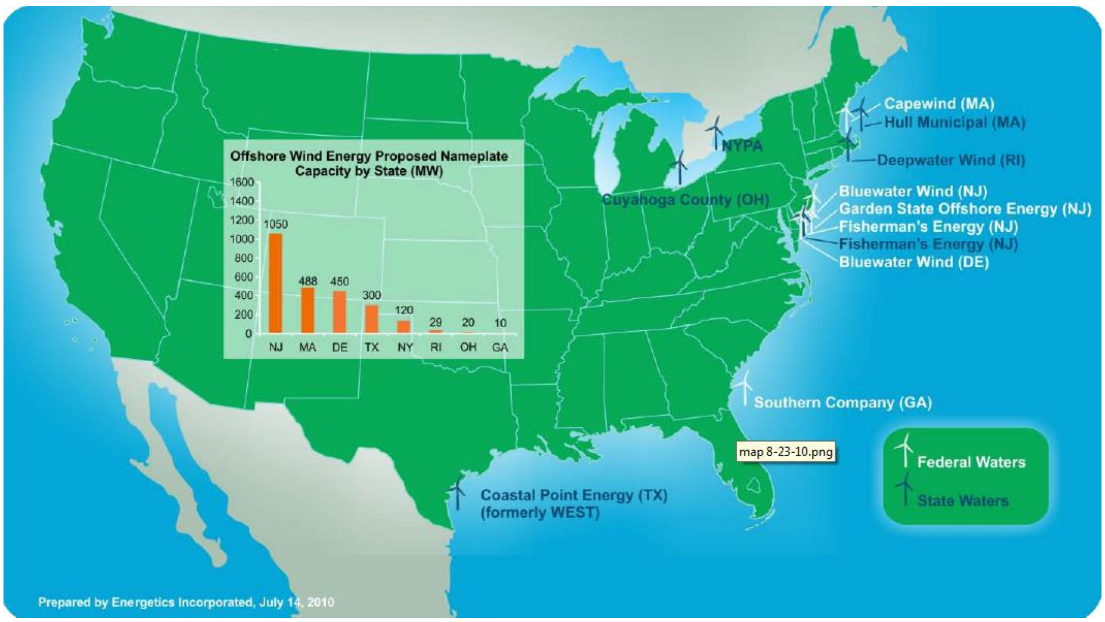


Figure 1-1 proposed U.S. offshore wind projects and capacity showing projects with significant progress[5]

1-1-2. Policies that support wind deployment

The rapid growth of wind energy in the U.S. during the past decade was highly driven by government policies at both the federal and state levels. “At the federal level, the most important policy incentives in recent years have been the Production Tax Credit (PTC), accelerated tax depreciation, and two American Recovery and Reinvestment Act provisions.” [6] The PTC gives a 10-year, inflation adjusted credit that equaled 2.2 cents/kWh in 2011 for wind power projects that would be in commercial operation by the end of 2012. The importance of PTC can be seen by the close correlation of the reduction of wind power capacity additions to the year PTC ended [7]. The PTC was extended at the start of 2013 [8]. The accelerated tax depreciation provided tax incentives for wind project owners who could depreciate most of the investment in a short period of time. Section 1603 of the Recovery Act established another policy incentive; it enabled wind power projects under construction by the end of 2011 and in service by the end of 2012 to receive either a 30% investment tax credit (ITC) or a 30% cash grant in lieu of the PTC. Another policy incentive from the Recovery Act is described in Section 1705, which gave loan guarantees for commercial wind power projects constructed before September 30, 2011. Beyond these financial promotions, the federal government has also put efforts toward improving wind project siting and permitting [9].

At the state level, twenty-nine states and the District of Columbia have mandatory Renewable Portfolio Standards (RPS) and eight states have renewable energy goals (REG). The RPSs and REGs have policies that promote renewable energy in order to reach the targeted penetration by a certain end date. According to the U.S. Department of Energy (DOE) projections, the current RPS programs will promote average annual renewable energy additions of roughly 4-5 GW/year (not all of which will be wind) between 2012 and 2020 [6]. In addition to RPS and REG, concern about the emission of global warming gases from the burning of fossil fuels has opened new carbon markets intended to mitigate the impact. The Northeast's Regional Greenhouse Gas Initiative (RGGI) cap-and-trade policy and California's greenhouse gas cap-and-trade program are two such markets, though their carbon trade price is currently too low to significantly advance large deployments of wind farms [6], [10]. Last but not least, wind energy projects are indirectly influenced by the assignment of Renewable Energy Zones (REZ). Although this policy is not nation-wide and explicit state-level REZs can only be seen in California, Colorado, Michigan, and Texas [9], it has sped up the construction of infrastructure, such as transmission lines, and mitigates possible opposition in advance, such as from wildlife impacts and visual disamenities [11]. Therefore, the uncertainty of wind farm construction and integration can be reduced, and planning and permitting times are expected to be shortened.

1-1-3. Key challenges facing offshore wind deployment

Despite wind energy's potential benefits, challenges to its widespread deployment remain. These include: safety, human health and amenity impacts, property value depreciation, wildlife and natural impacts, power system stability, and energy costs (seen in Table 1-1). Some of these topics have been improved by technology, such as improvement in blade and tower reliability, and innovation in blade heating and rotor shutdown monitoring due to ice accumulation. Some topics, such as cost of energy, will face less opposition as economies of scale occur. But most of these wind challenges require explicit regulation to decrease contention. The regulations through setback distance or relocation of wind farms can effectively mitigate the impact of wind farms on human health and amenity, property value, and wildlife and natural impacts (Table 1-1). This implies that careful analysis of different siting scenarios that elucidate issues related to these challenging topic areas can help identify means of progress for wind farm installation. An objective analysis in these topic areas requires a measurement method to inform and engage the stakeholders of a wind farm project so that decisions can be made with sufficient information.

Table 1-1 Key challenge of wind farm installation

Topics	Description	Possible solution	Mitigation from setback distance or relocation
Safety	Ice throw	Technology improvement	Not relevant
	Blade failure	Technology improvement	Not relevant
	Tower failure	Technology improvement	Not relevant
	Effect on aviation	Regulation	Significant
	Marine safety	Regulation	Significant
Human health and amenity	Noise	Regulation	Very significant
	Shadow flicker	Regulation	Very significant
Property value	Visual disamenity	Regulation	Very significant
	Sense of place or community	Regulation	Very significant
	Tourism impact	Regulation	Very significant
Wildlife and natural impact	Avian mortality	Regulation	Significant
	Migratory route of avian life	Regulation	Significant
	Impact on marine life	Regulation	Not significant
	Habitat destruction or fragmentation	Regulation	Not significant
Power system	Fluctuation of energy generation		Significant
	Integration cost		Not relevant
	Inefficiency of existing power plants		Not relevant
Cost of energy	Subsidies	Scale of economy	Not relevant
	Construction of support infrastructure	Scale of economy	Not relevant

1-2 Research questions and objectives

What is missing in the detailed analysis of the siting of offshore wind farms with regard to the key challenges facing their deployment? This question serves as the motivation that will guide the primary questions and objectives of this research. This section will briefly describe the research questions that will be explored in this dissertation, starting with how to estimate wind energy generation. Then, it will discuss how the life cycle environmental impact of an offshore wind farm could be measured. Next, it will ask how the external cost of visual impact could be quantified. Finally, it will examine how to systematically assess the competing objectives of offshore wind farms.

1-2-1. Predicting wind speed profiles at remote sites

Predicting energy generation is one of the most crucial and fundamental processes for an offshore wind farm project. A lack of wind speed profile data at planned locations of wind farms can cause a biased estimation and can directly affect the predicted cost of wind energy. Although installing a wind meter can reduce the uncertainty of wind speed estimation, the construction and operation of such a meter tower is costly, time-consuming, and can even be technically infeasible in some locations. Therefore, the first research question examines how to build a model that will help estimate wind energy generation at potential offshore wind farm locations, based on data collected at remote onshore sites.

1-2-2. Life cycle environmental impact of offshore wind farms

The research question addressed in the life cycle assessment of OWFs is to explore how siting in different counties and at various offshore locations influence the environmental performance associated with the material production, manufacturing, installation, operation and maintenance, and decommissioning stages.

The current evaluation metric commonly used for evaluating an offshore wind project is its levelized cost of energy [12], [13]. This metric doesn’t take environmental externalities into account, however. The negative externality of an offshore wind farm needs to consider the pollution generated throughout the wind farm’s lifetime, from manufacture, to installation, operation and maintenance and through to its decommissioning. The positive externality of an offshore wind farm includes the electricity it displaces from the grid and the consequent reduction in pollution due to the burning of fossil fuels. Thus, this research question focuses on how to measure and integrate the life cycle environmental impact of an offshore wind farm within traditional evaluation metrics.

1-2-3. Quantifying the local view shed impact of offshore wind farms

The research question is how to measure visual impact for different OWF siting alternatives and represent the impact in the form of a monetized unit.

One of points of contention that hinders offshore wind farms from successful deployment is local opposition to the visual impact of turbines, which can be as tall as 150 m [14]. Concerns over perceived detrimental visual impacts include reductions in tourism, local property values, and community harmony, along with a loss of scenic landscapes [9]. These concerns can even be intensified by the difficulty of measuring subjective aesthetic judgment [15]–[17]. Facing this situation, wind project developers and proponents are often unable to have productive discourse with project opponents and thus cannot reach a solution based on compromise. To provide informed impact analysis and help build consensus between both sides of a local wind farm siting debate, one of the research goals is to develop a method that combines objective spatial analysis of turbine visual impact and subjective values on visual disamenity. By utilizing the results generated from this method, offshore wind farm locations can be sited at the optimal distance from shore, such that increased installation cost does not outweigh the benefit of decreased visual impact when offshore wind farms (OWFs) are sited farther away from the coast.

1-2-4. Competing objectives and Need for Integrated Assessment

The most common metric used for OWF siting decisions is the levelized cost of energy, which includes the life-cycle cost of the project and total energy generation. The life cycle cost can be treated as an internal cost, while the generated energy can easily be transformed into a similar monetary unit and treated as a benefit. However, the externality of the OWF is not explicitly expressed in the decision making of a wind project. Quantifying the negative externalities, such as visual disamenity, and the positive externalities, such as displaced electricity pollution from burning fossil fuel, are crucial, and combing them with internal OWF cost/benefit assessments provide a complete picture of each OWF project's impact. The research goal, then, is to develop a systematic assessment framework that can incorporate the internal and external costs and benefits.

The development of new offshore wind farms is often a problematic process due to competing energy, economic, social, and environmental objectives, and thus requires interdisciplinary analysis (see Table 1-2) [18][19][20]. The major controversy surrounding the siting of OWFs results from tradeoffs associated with the proximity to the shoreline. Typically, siting wind farms close to shore is economically beneficial, due to lower installation costs in shallow water and less electricity loss, due to a shorter transmission distance [5]. However, locating OWFs close to the shore creates social resistance from changes to the local viewshed.

Table 1-2 Advantages and barriers of new offshore wind farms

Objectives	Advantages	Barriers
Energy	Reduces imported and non-renewable energy sources [5]	Intermittency of wind energy and limited transmission capacity [12] [21]
Economic	Higher and more stable wind resource farther from shore makes wind farms more economically beneficial [22]	Increased costs of foundation and transmission line costs further offshore [5]
Social	Public support for renewable energy as a climate change policy [23], [24]	Local communities dislike visual impact [25]
Environment	Reduction in the emissions of GHGs and other air pollutants [5][21][26]	Potential for negative impact on marine life and bird populations [27]

1-2-5. Research objectives

The main research objectives are to develop and apply a systematic integrated assessment methodology to determine optimal OWF siting in the Great Lakes and to develop methods that address trade-offs among stakeholder objectives. As a result of this integrated assessment, engineering design decisions will be determined (i.e. turbine height and foundation type) with respect to these multiple objectives.

1-3 Outline of dissertation framework

1-3-1. Framework

The integrated assessment, seen in Figure 1-2, will be organized into four chapters (Chapter 2 to 5) to evaluate candidate OWF areas (Oceana, Muskegon and Berrien Counties in Lake Michigan and Huron County in Lake Huron). **Chapter 2 (Use of Geostatistics to Extrapolate Wind Speed Profiles at Remote Sites via Known Meteorological and Geographical Data)** will create a regression to extrapolate the wind speed profile of a low-height measurement to that consistent with a wind turbine hub height. Then, a geostatistical model will be used to estimate wind speed patterns at remote offshore sites, based on the onshore measurements. In **Chapter 3 (Life-cycle Assessment for Offshore Wind Farm Siting)**, engineering decisions about the different physical characteristics of the turbines, towers, and foundations, along with their net energy generation impact, net GHG, and criteria air pollutants, will be captured in a life cycle model. The model will account for the operation phase, as well as the material extraction, manufacture, installation, and decommission phases of the OWF lifecycle in order to present a comprehensive assessment of its environmental sustainability.

Chapter 4 (Characterization and Valuation of Viewshed Impacts of Offshore Wind Farm Siting) will develop a model to account for the negative impact of OWF viewsheds using geographic information system (GIS) tools. It will then determine the quantitative indicator of social acceptability, based on population distribution and the external cost of the visual impact on the population. Finally, in **Chapter 5 (Multi-objective Analyses of Offshore Wind Farm Siting: An Integrated Assessment of Energy, Economic, Environmental and Social Factors),** an aggregated performance metric using energy, economic, environmental, and viewshed results from Chapters 2 to 5 will be created to identify the best solution for OWF development in the candidate areas. Several methods used to estimate environmental benefits of wind energy will be compared and discussed, since various evaluation approaches of multiple criteria are also adopted.

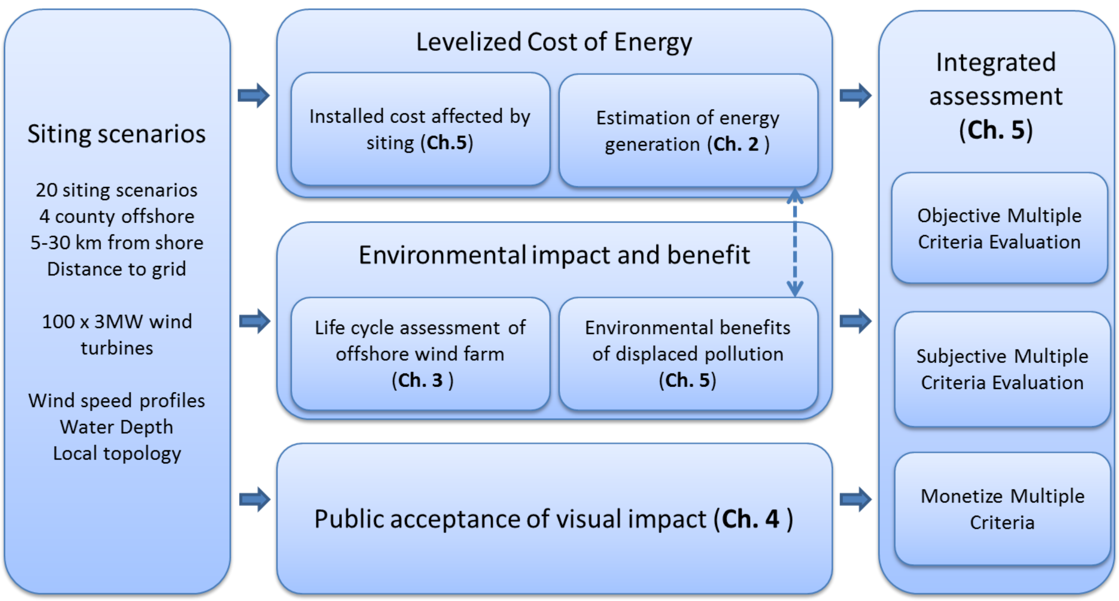


Figure 1-2 Research framework

1-3-2. Scholarly significance and impact

The study is expected to advance the scholarly understanding of OWF siting in the following ways:

- To use the geostatistical method to develop a wind speed profile estimation model based on known weather station data
- To develop a GIS based model to quantify energy generation, installation costs, and viewshed impact based on location

- To create a life cycle model of OWFs that considers different turbine blade and tower dimensions and different foundation options.
- To elucidate the tradeoffs among diverse factors, including energy efficiency, visual impact, infrastructure cost, and environmental benefits
- To enable stakeholders to make informed decisions about appropriate OWF sites

The results will help developers and local communities identify the most viable sites for OWF deployment. Mutual benefits could be achieved in some circumstances if developers could place wind farms near shore to improve financial performance by compensating communities for the affected viewsheds. The analysis of payment for impacted viewsheds in this study differs from prior research where only qualitative [25] [28] or questionnaire [15] methods were used to consider this externality. The final outcome will include life cycle, spatial, and quantitative characteristics in a performance index to better inform renewable energy policy, compared to simple economic analyses. The study will present the costs and benefits of new OWF sites, which could contribute to the achievement of a higher Renewable Portfolio Standard in Michigan.

Chapter 2

Use of Geostatistics to Extrapolate Wind Speed Profiles at Remote Sites via Known Meteorological and Geographical Data

Abstract

Wind speed profiles have been measured at a small number of sites, but wind power siting applications require estimates across a wider set of locations. Wind speed estimates are commonly extrapolated from the Weibull distribution for wind speed profile and from the power law equation for wind speed vertical gradient based on available data. The purpose of the study is to test the combination of two methods for predicting wind speed pattern at remote sites and at hub height. A regression model is built to estimate the value of a key power law parameter (the Helllman exponent) from site-scale factors. The power law estimate helps to produce accurate wind speed profiles at wind turbine height from observed weather station data. Next, a constant in the approximate Weibull distribution of the observed wind speed profile is extrapolated by a geostatistical model to help estimate wind speed profiles at unsampled locations.

The regression and geostatistical models are constructed based on the weather station data in the Great Lakes areas of Michigan, where hourly wind speed data for multiple years at hub height are measured. The model-predicted wind speed distribution is used to calculate the energy generation with a Vestas 3.0 MW wind turbine. The results show that the Hellman exponents ranged from 0.3 to 0.38 and that these estimates lead to more accurate extrapolations of the wind speed at 100 meter hub height. Moreover, the Weibull distribution with a shape parameter of 1.2 or of 1.4 was superior to the commonly used Rayleigh distribution, due to the lack of representing the wind speed variance in the latter model. By improving wind speed estimates as demonstrated, the combination of the power law equation and the Weibull

distribution can improve the prediction of wind energy potential and better help micro-siting of wind farms.

2-1 Introduction

Understanding wind speed distribution and estimating potential generation of wind energy of a wind energy turbine is important for the planning and implementation of wind power projects. Evaluations of wind energy generation are often conducted using wind speed data measured at hub height in order to evaluate the kinetic energy potential. Unfortunately, wind speed data are often not available at a desired location or hub height unless a meteorological tower is installed. But the installation of a costly, tall tower and the limited period of measurement can constrain the utilization of recorded data in estimating energy potential. To avoid this problem, another approach is adopted that takes advantage of long-term observations from existing weather station data and extrapolates wind speed distributions over time to hub height by considering wind shear effect (defined as the variation of wind speed across a plane perpendicular to the wind direction) and using a statistical model [29].

Wind estimation based on statistical models is supported by the availability of nationwide mean wind speed maps, such as AWS Truewind maps at different heights. When recorded data from weather stations are not available for proposed wind farm locations, average wind speed maps at coarse scale help to solve the siting problem by considering energy potential evaluation.

One statistical model widely used in estimating temporal variation in wind speeds is the Weibull probability distribution, which captures well the distribution of hourly wind speed over a year at any given site. By using a known mean wind speed and a 'shape parameter' k as variables in the Weibull distribution equation, the probability density of hourly wind speeds can be easily represented. When k=2, a special case of the Weibull distribution called the Rayleigh distribution is shown. The Weibull distribution, once obtained, can be used to calculate approximate wind energy available based on the observed wind speed data.

Measured wind data at weather stations is the more direct method to capture the characteristics of mean wind speed and wind energy potential, but extrapolation to account for wind shear, faster wind speed at higher heights, is required because the world standard for most wind speed measurements is too low (10 meters height) to capture wind speeds at hub height.

Wind shear extrapolation varies depending on the stability of air currents and roughness of the terrain. In a small geographical area, extrapolation can employ measured wind speed data of neighboring areas by considering the effect of ground roughness and terrain. Such extrapolation can be used to generate wind resource maps, and is the process used in the Wind Atlas Methodology[30] .

This study examines the feasibility of using the known meteorological and geographical data to predict wind profiles at remote sites and at hub height. To accomplish this, the first research question investigates what is the best representation of the shear effect for the weather station data to obtain wind speed distributions at 100 meter hub height. The accuracy of wind speed vertical gradient extrapolation is compared to the AWS Truewind mean wind speed maps. Next, we test the hypothesis that the Weibull distribution (especially the special case as Rayleigh distribution) represents wind profiles at sampled weather station sites with measured wind speed data. Comparison of the approximate Weibull distributions to observed wind data at sampled sites was used to test the suitability of the shape parameters. The shape parameter values are then taken as input into a geostatistical kriging model to predict shape parameter values at unmeasured locations. Once the wind energy generation is measured through the Weibull distribution and expressed for variation, the wind project location that is decided simply based on energy goal can be evaluated in terms of Risk of Return (energy generation per unit of variation/risk).

2-2 Literature review of wind estimation and geostatistical method

Wind shear is described as the variation of wind speed with elevation. Wind speed is slower at lower elevations due to friction of the natural environment or artificial obstacles on the ground. The two most common methods of estimating vertical wind speed gradient are the logarithmic law and the Hellman power law. Each of these two approaches emphasizes the influence of surface roughness. The log law can be described as the equation:

$$\frac{V(z)}{V(z_{\mathrm{r}})} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)}$$

where $V(z)$ is the wind speed at height z, $V(z_r)$ is the wind speed at reference height z_r and z_0 is the surface roughness length. The surface roughness length is a parameter used to characterize wind shear in the condition of the surface roughness elements with various heights. The typical values for different types of terrain have been estimated (Table 2-1) [31].

Table 2-1 Typical Surface Roughness Lengths [31]

Type of terrain	Roughness length Z_0[m]
Cities, forests	0.7
Suburbs, wooded countryside	0.3
Villages, countryside with trees and buildings	0.1
Open farmland, few trees and buildings	0.03
Flat grassy plains	0.01
Flat desert, rough sea	0.001

Following a similar concept, the empirically developed Hellman power law correlates wind speed at diverse heights and is expressed by:

$$\frac{V(z)}{V(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha}$$

where α is the Hellman exponent, 0.2 is given for the continental area, or approximately 1/7 with stable atmosphere[31]–[33]. Several studies [34][35][36][37] have previously indicated that the Hellman exponent does not accurately predict wind profile with the 1/7 power law. Instead, a significant variation results from terrain as well as location characteristics. Typical power law exponent values for different types of terrains have been observed using the roughness elements on the ground(Table 2-2) [38].

Table 2-2 Typical power law exponents for varying terrain [38]

Terrain Description	Power law exponent, α
Urban areas with tall building	0.4
Wooded country – small towns and suburbs	0.28 – 0.30
Many trees and occasional building	0.22 – 0.24
Tall row crops, hedges, a few trees	0.20
Level country with foot-high grass, occasional tree	0.16
Short grass on untilled ground	0.14
Smooth, hard ground, lake or ocean	0.10

The wind shear effect is not always accurately represented by the two mathematical models, particularly if the values of surface roughness length or the Hellman exponent listed above are directly applied to the models. In addition to terrains, many other factors can affect the extrapolation, including wind speed, the landscape features, the time of the day or season, pressure gradients, the temperature, and height.

To understand the efficacy of applying the wind shear model for different terrains, Ray et al. [39] compared combinations of three wind shear models and three approaches used to average the wind data. The goal was to more accurately extrapolate hub height mean wind speeds from the lower height wind data. The first approach in that study, called “overall mean,” uses mean wind speeds of two lower measured heights to calculate an overall wind shear parameter. The value of the wind shear parameter is then applied to the wind shear model to predict mean wind speed at hub height. Another approach used was the “parameter average” approach, which averages wind shear parameters derived from comparison of each paired wind speed observation. This averaged wind shear parameter is then used to extrapolate mean wind speed at hub height. The last “extrapolated time series” approach uses the wind shear parameter from each paired observation to calculate a wind speed time series at hub height. The overall mean wind speed at hub height is then averaged from the wind speed time series. By comparing the extrapolated mean wind speed and the measured mean wind speed at hub height, Ray et al. found that “overall mean” and “parameter average” outperforms “time series” for sites with flat terrain and for sites with hills of no trees. For sites with forests, all approaches performed equally well.

Another finding of Ray’s study is that the power law is as good as other methods in estimating wind speed vertical gradient. The author used three wind shear models, i.e., the log law, modified log law, and power law, to decide the optimal approach for each site. The fitness of the power law for wind shear effect shows no significant difference from log laws. This result is consistent with other studies of wind shear pattern in supporting the wide adaptation of the power law [35][36][40][41].

Using measured wind speed data at different heights to test the accuracy of a wind shear model is constrained by the availability of installed meteorological towers. To cope with this problem, one alternative for investigating variation of wind shear effect is to employ wind resource maps that shows mean wind speed at certain heights. These maps cover broad geographical areas. They can be compared with the lower height wind speed data available from existing weather stations. One of the well-known wind maps is generated by AWS Truepower, a renewable energy company that creates proprietary wind resource maps widely accepted by academia, governments (including National Renewable Energy Laboratory and the State of Michigan), investors and wind farm developers. These maps show the estimated wind speed at heights of 30m, 60m, 80m, and 100m above ground. To generate the maps, two atmospheric models, a mesoscale numerical weather prediction model, and a microscale wind flow model, are combined and include weather data from wide sources, including surface stations, rawinsonde stations, satellites, aircraft, geophysical data, and others [42]. The mesoscale simulations use full equations of air motion to depict the wind dynamics for a period of 366 days up to 15 years, with a 2.5km grid resolution. The microscale simulations then fine-tune the maps, taking into consideration wind shear exponents, local terrain and roughness at a resolution of 200m. Finally, these maps are validated with available mast data so that the reliability and validity can be improved. These publicly accessible wind maps from NREL and the Michigan website are therefore used in this research as the reference mean wind speed at hub height.

The mean wind speed at hub height can be used to estimate wind energy potential by multiplying the total wind kinetic energy to a given capacity factor. The capacity factor is a percentage that is defined as the energy generated during the year [MWh] divided by the product of the rated power [MW] and the number of hours in a year [h]. Using an approximate capacity factor to estimate wind energy potential, however, is not as accurate as measuring wind energy generation on the basis of wind speed distribution and matched power curve of a wind turbine at each working wind speed status. Consequently, wind speed profile data are helpful in accurately estimating wind energy potential. Among two widely used wind speed distribution models, Weibull and Rayleigh distribution, Jowder in 2006[43] showed that the Weibull distribution estimates the wind speed variation better than Rayleigh distribution function in the Kingdom of Bahrain. The study by Ulgen and Hepbasli [44] also indicated that the Weibull distribution is more suitable than the Rayleigh distribution to represent the actual probability of wind speed data in Izmir, Turkey, but the selection of the suitable shape and scale parameters for the Weibull distribution is key in the context of variation in site conditions.

The fact that the numerical values of the shape and scale parameters vary over a wide range is supported by Lun and Lam [45]. They investigated thirty years of hourly mean data for three different types of locations – an island area, a city area and a completely exposed area elevated in a city center in Hong Kong, and found the shape parameters varied from 1.63 to 2.03 and the scale parameters ranged from 2.76 to 8.92 [m/s]. All of these studies tend to suggest that the selection of the shape and scale parameters of the Weibull distribution to represent wind distribution should be adjusted based on the characteristics of local weather and terrain conditions.

Because the Weibull distribution is a function of the shape and scale (mean wind speed) parameters, the better the selection of parameters, the more accurate the measured wind speed profiles. For the wind profiles at hub heights at sampled weather station sites, they can be extrapolated from the measured ground level wind profiles using the power law. The extrapolated wind profiles can then be represented by a Weibull distribution. This extrapolation method is similar to the methods developed by Ray et al.[39] and Lubitz[41]. They compare measured mean wind speed at hub heights with the extrapolated mean wind speed using the Hellman exponent and power law. The whole process contributes to the construction of a Weibull wind distribution model with optimal parameters so that an accurate wind speed profile can be determined at a hub height higher than that of a weather station.

Once the individual Weibull distribution is validated as the representative wind speed profile at each weather station site at hub height, the so-called Wind Atlas Methodology can be applied to interpolate or extrapolate the wind profiles to other remote sites. The same approach is used by the well-known proprietary software WAsP [46]. In the software, the generalized wind climate at a higher elevation is deduced from the measured wind profile at a lower elevation by removing the effects of local terrain; it is then used to determine the location of interest by adding the effect of its terrain features. Due to the homogeneity and gradient change of wind profiles at higher elevations (a lack of dramatic change in ground friction), wind profiles are varied more smoothly and affected by geographical weather differences. Thus, wind profiles that are close to one another tend to be more alike (implying similar scale and shape parameters in the Weibull distribution) than those that are farther apart. According to this geographical characteristic, geostatistical analyses, such as Kriging, then provide a possibility to predict the unknown wind profiles and their uncertainties at remote sites based on the known Weibull distributions at weather stations.

2-3 Vertical and horizontal wind pattern extrapolation by regression and geostatistical models

In order to develop a methodology using known weather station data to predict wind energy potential at hub height at remote sites, a framework of study is organized and examined in terms of each step required to predict wind energy (Figure 2-1). The lower part of the figure shows the process of regression modeling to predict the Hellman exponent. Data are collected and processed to represent the independent variables used for predicting the dependent variable Hellman exponent (vertical extrapolation). The upper part of the figure shows the geostatistical analysis. This sub-model uses the statistical distribution of wind speed at a weather station to predict wind profiles at the remote sites (horizontal extrapolation).

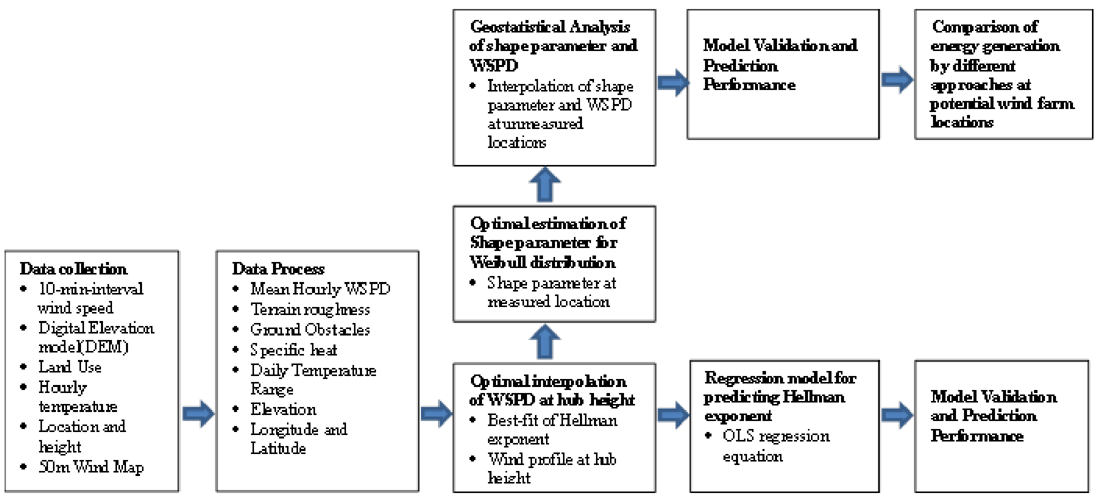


Figure 2-1 Research framework of wind profile estimation

2-3-1. Data collection and process

Ground level meteorological data collected by weather stations are more complete than data measured by a temporary mast because the former have a longer record of information and cover a wider area. The weather station data are classified into several categories that may affect wind energy prediction. The weather station data recognized by National Climatic Data Center meets the current study needs, including hourly/sub-hourly observed data on wind speed, temperature and other locational station characteristics such as elevation, longitude and latitude [47]. A total of 103 weather stations located in the State of Michigan are considered the sample for the regression model. Meanwhile, the universal average wind speed data at higher elevation are derived from AWS Truewind produced and NREL validated wind map of 50 meter elevation [22]. The wind map was generated from a raster dataset with a 200 m resolution. To compare an extrapolated wind profile with one measured at hub height, wind speed profiles at different elevations are acquired from the Anemometer Loan Program at Michigan State University [48]. This program has measured 21 locations, five of which contain complete 10-min wind speed data series for a whole year at an elevation higher than 50 meters. These will be used to validate the accuracy of the prediction model that is used to obtain the wind speed profile at hub height.

Also used in the study are terrain, land use and wind turbine specification data. The topography was derived from the U.S. Geological Survey (approximate 90 x 90 meter resolution) National Elevation Dataset (NED). The wind turbine specifications came from Vestas 3.0 MW offshore wind series. The 30 x 30 meter land cover data were obtained from National Land Cover Database 2006 (NLCD2006). Since the wind speed at one particular location is affected by the neighboring terrain and land covers (ground obstacles), a terrain roughness index calculated from raw data is used to represent this influence.

The index of terrain roughness R is defined as the variance of raster heights from the NED measurement at 90 x 90 meter cells in a circle window with a 50km radius centered on a sample location. We hypothesize that the variation in the Hellman exponent or wind shear effect at a weather station is affected by terrain characteristics over this broader area (Table 2-3). Similarly, to demonstrate the influence of ground obstacles on the wind shear effect, ground obstacles F is defined as the weighted counts of certain developed and forested land use types at 30 x 30 meter cells in a circle window with a 50km radius centered on a sample location. The weights given to each cell is based on the comparative influence of land cover types on wind shear effect. The percentage of impervious surface in relation to the total cover in built areas is hence transformed to a relative value to indicate the potential reduction of wind speed at ground level. The relative numbers are also applied to forest areas where a higher weight is given to cells with a land cover type of evergreen forest as opposed to deciduous forest because evergreens produce a rougher canopy. Moreover, to show the possible influence of water coverage on the wind shear effect, an index of specific heat capacity, designated as C, is defined as the sum of numbers given to cells of land cover type as water body at 90 x 90 meter resolution in a circle window with a 50 km radius centered on sample location. Land cover types that contain whole or partial water bodies include areas such as Open Water, Woody Wetlands, and Emergent Herbaceous Wetlands. Cells in these areas are given the relative numbers 10, 3 and 2 individually based on the level of water abundance.

Table 2-3 Definition, data source and measurement of explanatory variables in the regression model of Hellman exponent

Variables	Definition, Data and Measurement
Latitude(L)	Decimal degree of latitude at sample location. National Climate Data Center(NCDC)
Longitude(G)	Decimal degree of longitude at sample location. National Climate Data Center(NCDC)
Elevation(H)	Meter height of weather stations. National Climate Data Center(NCDC)
Specific heat capacity(C)	Sum of numbers given to water body type at 90*90 meter cells in a circle window with 50 km radius centered on a sample location. National Land Cover Database 2006(NLCD2006). Open Water:10; Woody Wetlands:3; Emergent Herbaceous Wetlands:2; Others:0.
Variation of temperature(T)	The average of daily temperature range in Celsius at a sampl location. National Climate Data Center(NCDC)
Ground mean wind speed(W)	The average hourly wind speed in meter/second for sampled stations generally mounted 10meter above the ground. ASOS
Terrain Roughness(R)	Variance of raster height from DEM measurement at 90*90 meter cells in a circle window with a 50 km radius centered on asample location. National Elevation Dataset(NED)
Ground Obstacles(F)	Sum of numbers given to land use types at 30*30 meter cells in a circle window with a 50 km radius centered on a sample location. National Land Cover Database 2006(NLCD2006). Developed High Intensity:24; Commercial/Industrial/Transportation:16; High Intensity Residential:9 ; Low Intensity Residential:1; Deciduous Forest:6; Mixed Forest:9; Evergreen Forest:12; Others:0.

2-3-2. Regression model for wind shear effect

A regression model was constructed to determine the relationship between eight explanatory variables and the Hellman exponent. The dependent variable, or observed Hellman exponent at each station locations, was derived from the measured mean hourly wind speed data at ground level ($\sum_{i=1}^{8760} V_i(z_r)$) and the NREL/AWS Truewind wind speed map at the same location and hub height ($\bar{V}(z)$). Based on these measurements at each hour and each location, we calculated the Hellman exponent α as:

$$\min \bar{V}(z) - {z}/{z_r} \sum_{i=1}^{8760} V_i(z_r)^{\alpha} / 8760$$

The measured hourly wind speed data are either from the average of measured 10 minute wind speed or directly provided by weather stations. The estimated Hellman exponent values can be applied to the power law equation so that the average of extrapolated hourly wind speed is equal to mean wind speed presented by the wind map of NREL/AWS Truewind.

The regression modeling started with the bivariate analysis of all dependent and independent variables. In addition to showing the matrix correlation of each pair of the variables, scientific knowledge is considered in the selection process of the explanatory variables. Next, SAS software was used to select a combination of critical predictors based on three methods: backward elimination, forward selection and stepwise procedures. Several statistics, including the adjusted R2, PRESS, Cp and Akaike's Information Criterion (AICs), were examined among possible models to evaluate fitness of the model to the observed data. Beside the overall model performance, the significance of individual predictors was also tested according to the *p*-value of *t*-statistics. In addition to the adjusted R-square, several indices are examined for selecting the model. The predicted residual sum of squares, denoted by PRESS, measures the model n times (number of observations), each time leaving out one observation and using the prediction equation $\hat{y}_{i,-i}$ to predict that observation. The difference between the prediction equation y_i and $\hat{y}_{i,-i}$ is squared and summed. This equals

$$PRESS = \sum_{i=1}^{n} \left(y_i - \hat{y}_{i,-i}\right)^2$$

The index is commonly known as a method of cross validation.

The model diagnosis focuses on outliers, multicollinearity and residuals. The purpose of detecting outliers is to measure the influence of each observation on the estimates. Influential observations are detected by Cook's D. Cook's D values greater than the absolute value of two are further investigated. Another method to examine the outliers is RSTUDENT. The studentized residuals checks whether the model are significantly different if an observation is removed. A RSTUDENT whose absolute value is larger than two needs further examination. FBETA and DFFIT are also conducted to see the influence of one observation on the fitness of the selected explanatory variables and on the performance of the dependent variable separately. Different from the tests for outliers that influence the overall model, the DFBETAS summarizes the effect of the observations on a particular parameter's coefficient. Each parameter in the model hence has a corresponding DFBETAS. To avoid multicollinearity, a variance inflation factor (VIF) is checked to see the existence of the redundant variables. Generally accepted, a VIF value larger than 7.5 is problematic [49]. Local multicollinearity is also investigated by the geographically weighted regression (GWR). Since the ordinary least squares (OLS) regression model was adopted, the observed data should meet the assumptions of linear regression. The residuals associated with each observation need to be examined in several assumptions, including unbiased, linearity, independence and identical distribution, normal distribution, homoscedasticity, and the lack of spatial correlation. The unbiased assumption requires a mean residual equal to zero. Linearity means that the relationship between the predicted and observed Hellman exponent should be linear. Independence indicates that the residual associated with one observation are not correlated with the residuals of any other observations. Errors that are not identically and independently distributed can make the *t*-test of coefficient estimation valid. Homoscedasticity assures the residual variance is constant among observations. Residual independence can be tested using the chi-squared test statistic. In the Shapiro-Wilk W test for normality, the p-value is measured assuming that the distribution is normal. Spatially uncorrelated residuals are residuals that are independent, meaning unrelated to each other based on spatial location.

Considering the spatial characteristics of the studied model parameters, an assumption that the residuals are not spatially correlated is required to assure stationary prediction across Michigan. Two methods, the Global and Local Morans' I tests, are used to test the residual variation across the studied area. The Global Moran's I tests whether the distribution of an attribute (i.e. residuals) is dispersed, random or clustered. Besides the global distribution of residuals being examined, the local Moran's I testing is conducted to see if residuals are surrounded by similar residual values (i.e. high surrounded by highs) or by different residual values (i.e. high surrounded by lows).

2-3-3. Geostatistical analyses for wind speed profiles

To estimate wind speed profiles at locations without weather stations, a geostatistical analysis is used to interpolate or extrapolate the Weibull distribution parameters within the range of a set of known weather station points. After estimating wind profiles for hub heights discussed in the previous section, the inter/extrapolation of the wind speed profiles at remote sites through nearby stations can be treated as a method focusing on horizontal estimation. Based on the rule that things that are close to one another are more alike than those that are farther apart, wind speed profiles at remote sites can be inter/extrapolated by those at nearby sites. The shape parameter of the Weibull distribution at 35 sites was examined to see if the data are normally distributed and the lack of the spatial cluster is presented. Several Kriging methods with modification of semivariogram and anisotropy were then compared to test for better model performance. Next, the best model is cross validated to measure prediction error and test for bias in predictions.

Data collection and the shape parameters

Hourly wind speed data of year 2011 from 35 weather stations are first selected. They are transformed based on the power law to represent wind speed profiles at hub height. An approximate Weibull distribution function is selected to match each wind speed profile. The parameters of the Weibull distribution for each profile were estimated individually based on

$$F(v) = \exp\left(-\left(\frac{v}{c}\right)^{k}\right)$$

where *F(v)* is the cumulative probability (time) for which the hourly mean speed exceeds *v*. The function is characterized by a "scale parameter" *c* and a "shape parameter" *k*. Their relationship with annual mean wind speed $\bar{v}$ can be expressed by:

$$\bar{v} = c\Gamma(1 + 1/k)$$

where Γ is the complete gamma function. The value of $\Gamma(1 + 1/k)$ can be derived by

$$\Gamma(z) = \int_0^{\infty} e^{-t} t^{z-1} dt$$

or an alternative definition:

$$\Gamma(z) = \frac{1}{z} \prod_{n=1}^{\infty} \frac{\left(1 + \frac{1}{n}\right)^{z}}{1 + \frac{z}{n}}$$

The two parameters (c and k) and Weibull function describe the characteristics of wind speed profiles at hub height at each station. Since the average wind speed is available from NREL wind maps, the focus in the study will be put on the estimation of the shape parameters. The shape parameters are treated as an explanatory variable and examined for normal distribution and spatial trend throughout the study area.

Exploratory spatial data analysis

The dataset of the shape parameter variables is examined to see a normal distribution by histograms and the skewness value because Kriging can be used efficiently with the normally distributed spatial data. Next, the spatial dependence of variables and data outliers is analyzed from the semivariogram surface map. Finally, the explanatory variables are plot in a 3-D coordinate to detect trend in the data. If the data present a specific trend, the assumption about data stationarity is violated.

Interpolation methods

After the presentation of exploratory spatial data analysis graphs, several interpolation methods are compared to see the best fitted one in predicting the shape parameter. Three geostatistical interpolation methods, including simple kriging, ordinary kriging and universal kriging, are conducted based on geostatistical procedures. Kriging is a generic name used to represent a family of generalized least-squares regression algorithms. The basic form of the linear regression estimator *Z*(u)* is defined as

$$Z^*(u) - m(u) = \sum_{\alpha=1}^{n(u)} \lambda_\alpha(u)[Z(u_\alpha) - m(u_\alpha)]$$

where $\lambda_\alpha(u)$ is the weight assigned to datum $Z(u_\alpha)$ interpreted as $Z(u_\alpha) - m(u_\alpha)$; $m(u)$ and $m(u_\alpha)$ stand for the expected value of $Z(u)$ and $Z(u_\alpha)$. Simple Kriging (SK) considers the known and constant *m(u)* value throughout the study area. Ordinary Krigng (OK) accounts for the unknown local mean by using the averaged *m(u)* from nearby $Z(u_\alpha)$. Therefore, OK compared to SK tends to reflect the data fluctuation within search neighborhoods and estimates values that are farther away from the overall mean. Universal Kriging (UK) considers an unknown local mean that smoothly varies within each local area. This is often used to represent a trend throughout study area with an analytical trend function. Convincing physical justification is required in order to apply UK.

Each Kriging interpolation technique is conducted based on an experimental semivariogram model. Several terms, including range, sill, nugget effect, model form and anisotropy, are associated with and tested for building a permissible semivariogram model. The range describes the distance between pairwise data points where the value difference reaches a threshold (sill). Sill consists of partial sill and nugget, and is the level of stable variance beyond distances over which values are spatially autocorrelated. Nugget effect considers measurement error and microscale variation, meaning that value difference exists even if measured points are at the same spot. Model forms are the curve used to describe the semivariogram change along with the lag (distance between each pair of data points) in the range. Alternatives include Gaussian, Stable, hole effect, K-bessel, J-bessel, exponential, circular, spherical, tetraspherical, and pentaspherical forms. Anisotropy is used to describe a phenomenon that semivariogram (pattern of spatial variability) changes with direction. All these terms in the semivariogram model are analyzed by a trial-and-error method to find a best fitted model based on the least root mean square error (RMSE).

Cross-validation and validation

The interpolation methods are diagnosed for prediction errors. The prediction errors are measured by comparing the observed value and predicted value, produced from withholding one data sample and then making a prediction for the same data locations. The mean prediction error is better near zero, meaning the prediction errors are unbiased. The smaller RMSE is also expected, meaning that predictions are close to the measured values. In addition, the assessment of uncertainty is expected to be valid. If the average standard errors are close to the RMSE, the variability in prediction is correctly presented.

Uncertainty and energy return per risk unit

To evaluate the uncertainty of the shape parameter prediction, a map is generated to show the predicted value ± 2 times the prediction standard error at a 95% confidence level, based on the assumption that the data is normally distributed.

The intermittent nature of wind energy generation is one critical issue for wind energy projects. Once the best extrapolation method is determined, it is applied to predict wind energy potential and the variation. By combining the average wind speed and the predicted shape parameter map, the implication of return for risk unit can be applied by showing the ratio of average energy generation and one unit of its standard error. Here energy return per risk unit is defined as averaged energy generation divided by the largest prediction variation range with respect to one standard error of the predicted mean wind speed and the shape parameter of the Weibull distribution. Further implication of the efficiency frontier can be made on an energy return per risk unit, which is defined as the average energy generation $E\mu$ divided by the prediction variation Ev. Since Ev is affected by the variation of the average wind speed and the shape parameter, its calculation includes the factors, defined by:

$$Energy\ Return\ per\ Risk\ Unit = \frac{E_\mu}{E_v} = \frac{E_\mu}{E_{max} - E_{min}}$$

where *Emax* means the relatively large wind energy potential under the estimation of the Weibull distribution with the scale parameter about one standard error above the mean wind speed and the shape parameter about one standard error above the averaged estimation, and *Emin* means the relatively small wind energy potential under the estimation of the Weibull distribution with scale parameter about one standard error below the mean wind speed and the shape parameter about one standard error below the averaged estimation.

2-4 Results

In this section, first, the effect of using theoretical methods on estimating wind characteristics is presented. The power law and the Weibull distribution are respectively applied at those Michigan weather stations where vertical wind shear and wind speed profiles are calculated. Next, the Hellman exponent of the power law is decided through a regression model. The accuracy of the model is presented, and it indicates that known spatial data are good references for Hellman exponent estimations. Finally, predicting wind profiles at remote sites is shown in terms of combining the Weibull distribution and geostatistical analysis.

2-4-1. Characteristics of wind speed in Michigan

The Hellman exponent is calculated by matching the average of extrapolated hourly wind speed to that of the NREL/AWS Truewind wind map for weather stations. The Hellman exponent assessment result shows that the Hellman exponent varies from 0.13 to 0.67. As shown in Figure 2-2, only one site presents a value close to the commonly used 1/7 law (about 0.14). The assessment, however, shows a wide range of Hellman exponent variation across space, but not surprisingly, the smallest value of the Hellman exponent is found at the mouth of Saginaw Bay, where ground friction is less influential than other onshore sites.

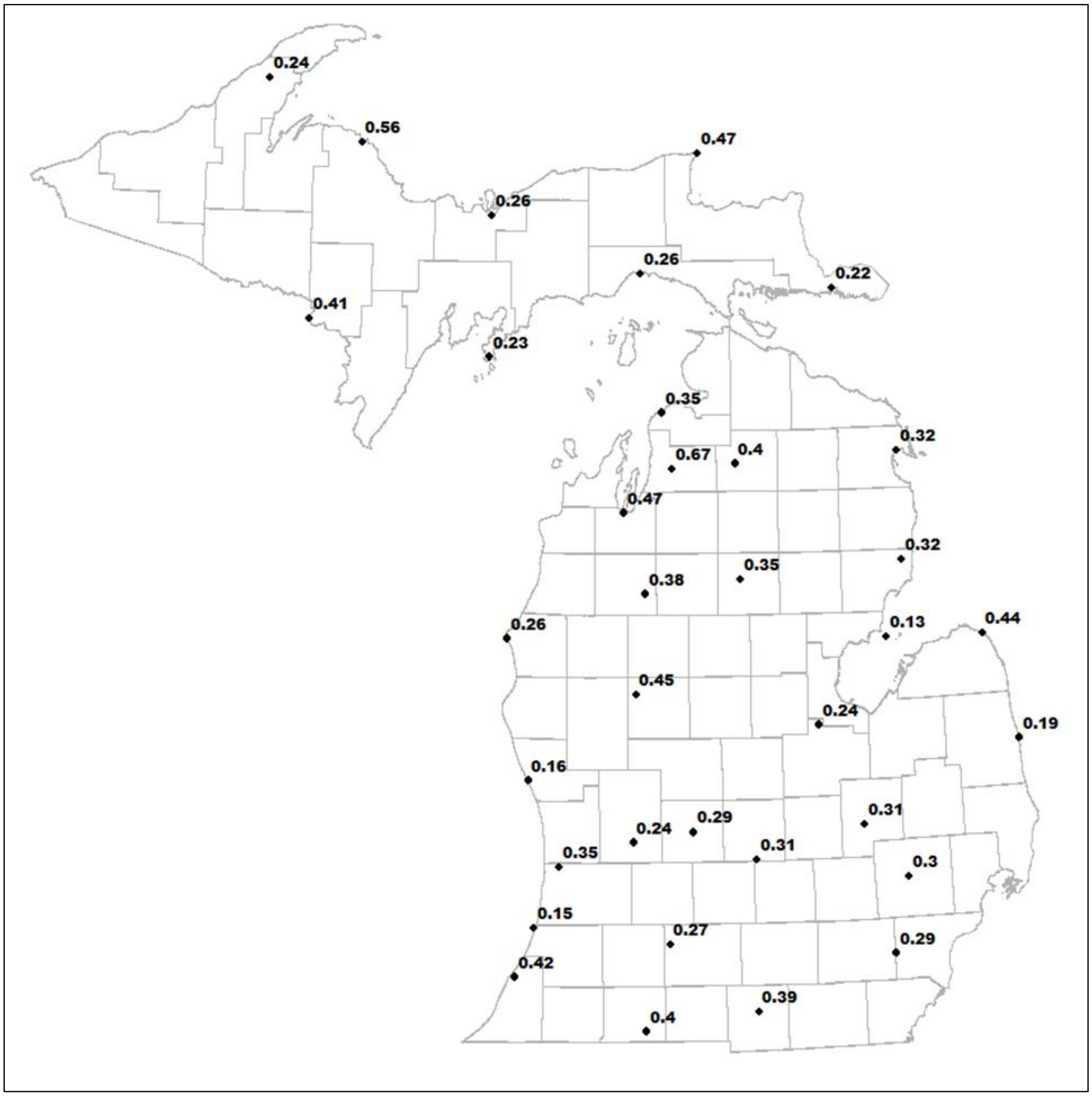


Figure 2-2 Hellman exponents at 35 weather stations

In the areas without measured data, wind speed profiles are usually extrapolated using the Weibull distribution with a shape parameter of 2. This statistical model tends to underestimate the percentage of low speed wind, and this is not exceptional in most of the studied sites. The wind profiles calculated by different approaches at the SJOM4 weather station show that replacing the shape parameter 2 with the best-fit number 1.4 in the Weibull distribution seems to produce a wind speed distribution more close to the measured data (Figure 2-3).

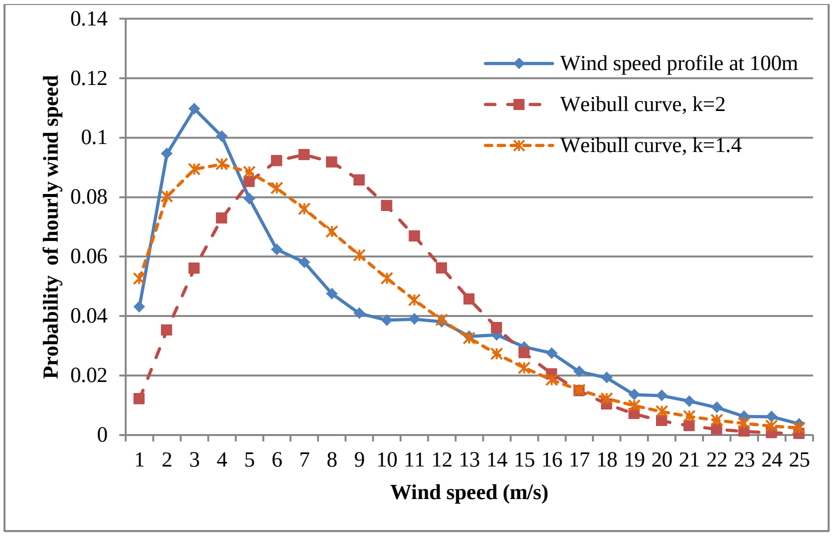


Figure 2-3 Probability of hourly wind speed by different approaches at the SJOM4 weather station

2-4-2. Regression model for vertical estimation of wind speed

Characteristics of variables

All variables used in the regression model for the Hellman exponent estimate are plotted in the form of histograms, normal curves and kernel densities (Figure 2-4). The frequency of the dependent variable (the Hellman exponent) among the 35 sampled weather stations substantially meets the normal distribution. The frequency of most explanatory variables presents a similar trend, except that the distribution of the terrain roughness variable skews to the right and variables of specific heat capacity and elevation show flatted distributions.

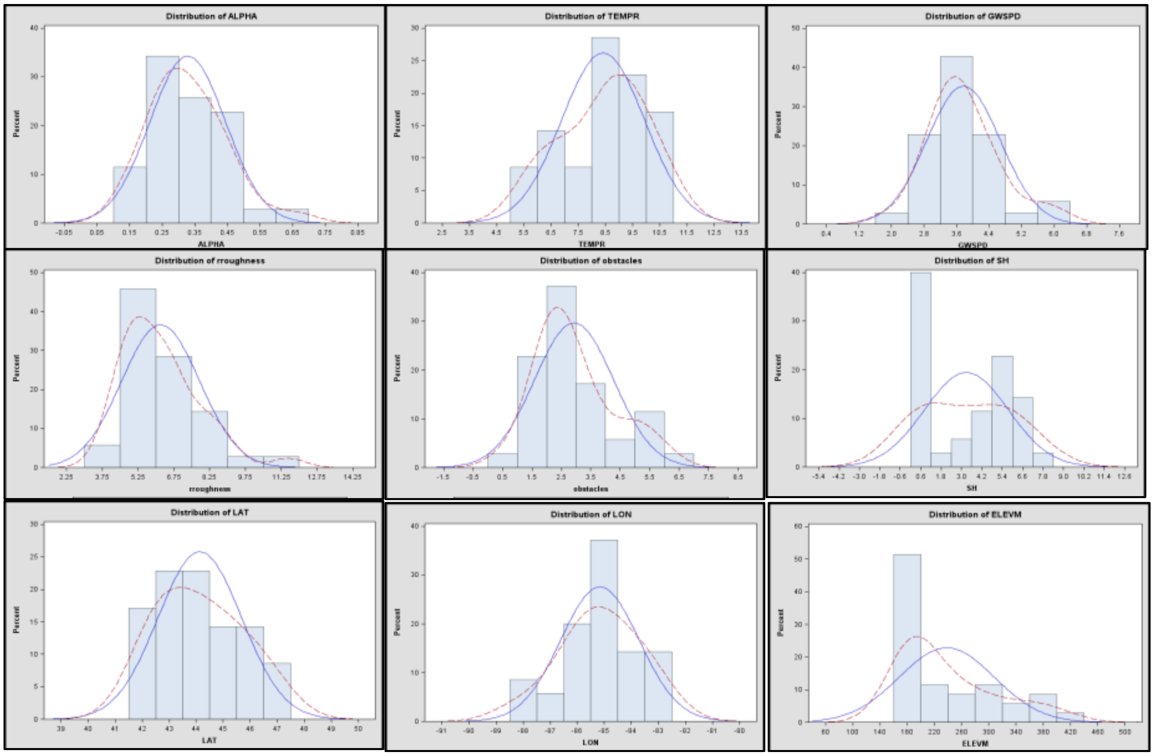


Figure 2-4 Frequency of all regression model variables (from top-left to bottom-right, Hellman exponent, temperature variation, ground mean wind speed, terrain roughness, ground obstacles, specific heat capacity, latitude, longitude and elevation) in the form of histograms, normal curves (blue lines) and kernel densities (dashed red line)

Bivariate analysis indicates that a moderate correlation can be found between the Hellman exponent variable and explanatory variables, including terrain roughness, ground mean wind speed, temperature variation, and ground obstacles (Figure 2-5). Meanwhile, possible correlations may exist between the variables of ground mean wind speed and temperature variation and between the variables of temperature variation and ground obstacles. In general, however, there is no significant correlation between explanatory variables. This avoids the potential multicollinearity of explanatory variables.

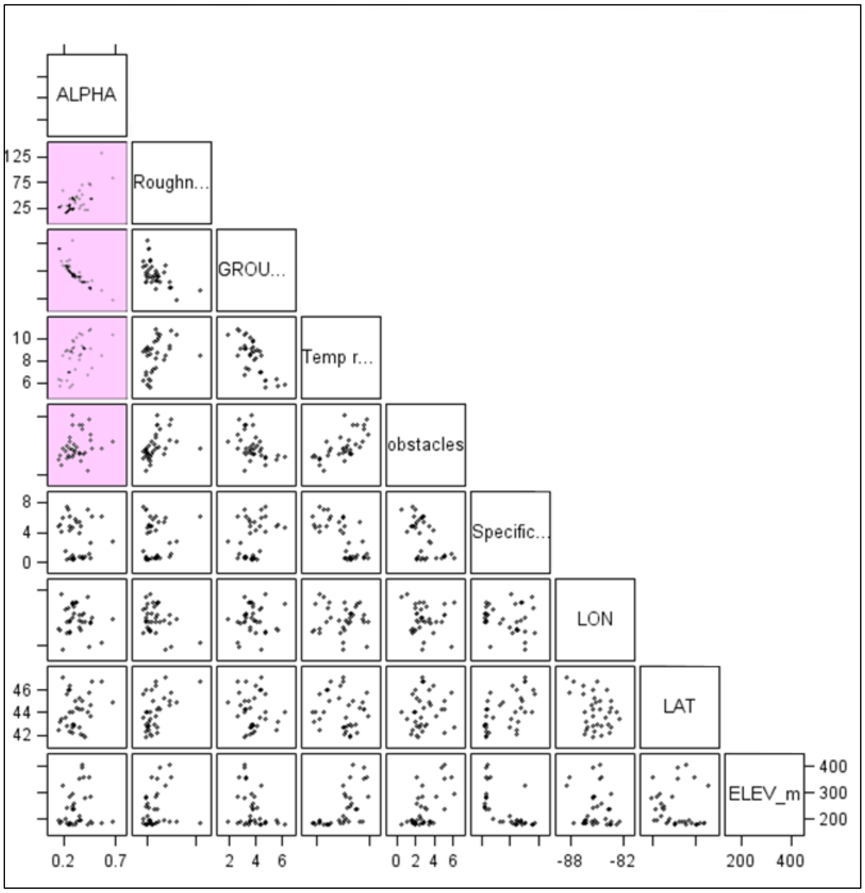


Figure 2-5 Matrix correlations between variables. Variables that are correlated are indicated in grey highlighting

Model building and fitness

Selecting the most representative variables for the OLS regression model is conducted by a stepwise procedure and refers to the results of the bivariate analysis. While adjusted R-square is considered to be the metric for model performance, three explanatory variables in the model can account for 88% of the Hellman exponent variation (Table 2-4). This performance is as good as those models having more explanatory variables. In other words, the model with explanatory variables of terrain roughness, ground mean wind speed and temperature variation concisely and effectively describes the variation of the Hellman exponent variable.

Table 2-4 Different model efficiency using different combinations of explanatory variables (only the top ten highest adjusted R-Square results are shown)

Number in Model	Adjusted R-Square	R-Square	Variables in Model
5	0.8985	0.9135	rroughness GWSPD TEMPR obstacles LAT
6	0.8871	0.9070	rroughness GWSPD SH LON LAT ELEVM
5	0.8868	0.9035	rroughness GWSPD obstacles LON LAT
4	0.8862	0.8996	rroughness GWSPD TEMPR LAT
5	0.8859	0.9027	rroughness GWSPD TEMPR LON LAT
4	0.8846	0.8982	rroughness GWSPD TEMPR ELEVM
5	0.8833	0.9005	rroughness GWSPD TEMPR LON ELEVM
3	0.8828	0.8931	rroughness GWSPD TEMPR
5	0.8808	0.8983	rroughness GWSPD TEMPR SH ELEVM
4	0.8806	0.8946	rroughness GWSPD TEMPR SH

Estimating the Hellman exponent by the fitted model is then achieved by

$$\alpha = 0.947 + 0.013R^{1/2} - 0.133W - 0.023T + \varepsilon$$

Further results of model fitness can be seen in Table 2-5; the *F* statistic for the overall model is highly significant (*F*=86.33, p<0.0001), indicating that the model explains a significant portion of the variation in the data. The conclusion is consistent with those based on the value of R-square and adjusted R-square. In addition, the t statistic for each predictor is also very significant (at each *t* value, p<0.05), indicating that the coefficients are different from zero. This result is supported by the bivariate analysis, in that the Hellman exponent is moderately correlated to three selected predictors.

Table 2-5 Fitness of regression model with three explanatory variables

Analysis of variance				
F value	86.33	Pr >F	<0.0001	
R-Square	0.893	Adjusted R-Square	0.883	
Parameter estimate				
variable	Parameter estimate	Standard error	*t*-value	Pr> $\lvert t \rvert$
Intercept	0.947	0.105	9.06	<0.0001
Roughness	0.013	0.005	2.52	0.0172
GWSPED	-0.133	0.012	-10.87	<0.0001
TEMPR	-0.023	0.007	-3.44	0.0017

The small PRESS value of 0.067 in this study means that the model predicts the observations well even though one observation is not used to fit the model. Another related method reports an index, denoted as *Cp*, which describes how well each model fits compared to the full model with all the predictors. The value of *Cp* in this best-fitting model equals 4 (the same as the number of parameters), and it indicates a better fit.

Model diagnosis

Outliers and influential analysis

The result of the study of residuals indicates that only one observation showing Studentized residuals larger than 2 and Leverage larger than 0.23 can be categorized as an outlier (Figure 2-6).

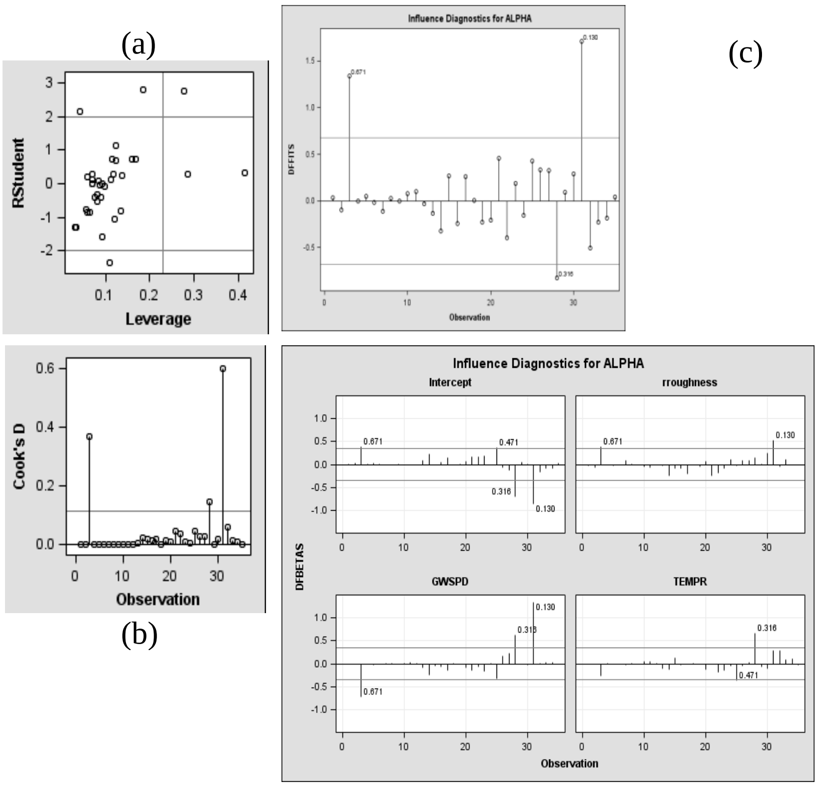


Figure 2-6 Statistics test for influential outliers (a) Studentized residuals and Leverage (b) Cook's D (c) DFFITS (d) DFBETAS

Three observations were slightly above the cut-off criterion for Cook's D > 4/35 (Figure 2-6). The result of the DFFITS test indicates three influential observations having a DFFITS value larger than the cut-off point of 0.7 (DFFITS > $2(p/n)^{1/2}$).

Most of the observations don't have the DFBETAS value above a cut-off value of 1, except one observation having suspected influence on the coefficient of the ground mean wind speed parameter (observation with alpha value equals 0.130).

Testing for Multicollinearity

The largest VIF is from the predictor of the Ground Wind Speed and is 2.6

Table 2-6). That is, the standard error for the coefficient of the GWSPD predictor variable is 1.6 times ($\sqrt{2.6} \approx 1.6$) as large as it would be if that predictor variable were uncorrelated with the other predictor variables.

Table 2-6 The Variance Inflation Factor test of the model predictors

Parameter Estimates							
Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Variance Inflation
Intercept	Intercept	1	0.94702	0.10451	9.06	<.0001	0
rroughness	rroughness	1	0.01266	0.00503	2.52	0.0172	1.44541
GWSPD	GWSPD	1	-0.13342	0.01228	-10.87	<.0001	2.64481
TEMPR	TEMPR	1	-0.02306	0.00671	-3.44	0.0017	2.23579

Residual examination

To verify whether the data meet the assumption of linear regression, several assumptions are considered, including linearity, normality, homoscedasticity, independence and a lack of spatial autocorrelation. The data verification plots of the predicted values versus either the residuals or studentized residuals exhibit no obvious pattern, indicating the effectiveness of the linear regression model (Figure 2-7). Further support of the linear regression can be seen on the plot of the predicted values versus the measured Hellman exponent alpha, indicating that the model successfully predicts the behavior of the estimator. Furthermore, the normal quantile plot of the residuals and plot of the residual histogram are consistent with the assumption of Gaussian errors, meaning that the distribution of residuals meets the general assumption of a linear regression model. Lastly, the "Residual-Fit" (or RF) plot shows that the spread in the residuals is no greater than the spread in the centered fit. All these plotting results substantially sustain the assumption that the relationships between the predictors and the estimator tend to be linear.

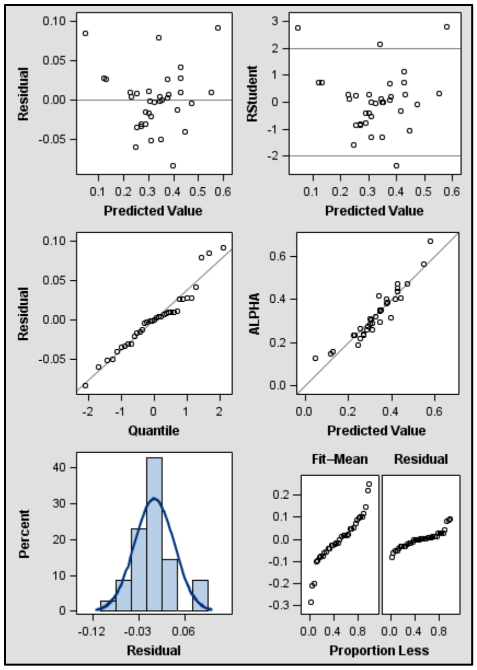


Figure 2-7 Fit diagnostics for the linear regression model of the Hellman exponent

The test for homoscedasticity (Figure 2-8) indicates that the explanatory variables do not present better accuracy in estimating the Hellman exponent when their values are smaller or larger.

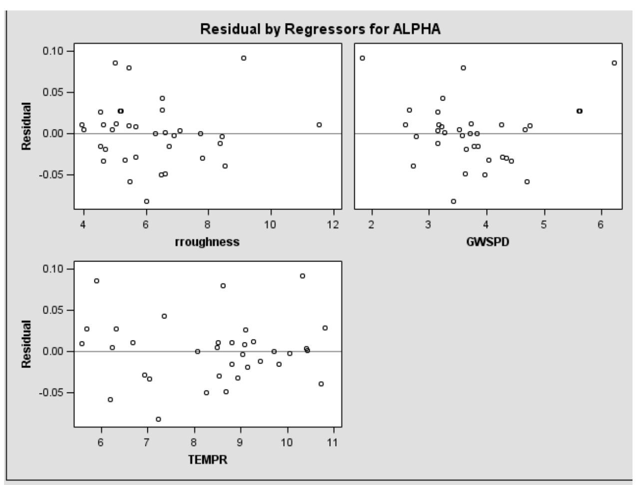


Figure 2-8 Distribution of prediction residuals versus explanatory variables of the Hellman exponent

The result of the chi-squared test for residual independence in this regression model shows that critical value of Chisq is 8.37 and its probability greater than Chisq value of 0.497 is greater than 0.05. This supports the null hypothesis that the variances of the residuals are homogeneous and residuals are not dependent. Meanwhile, this confirms one of the linear regression model assumptions that the residuals are independent and identically distributed.

The hypothesis of a random residual distribution cannot be rejected because the p-value is larger than 0.05, indicating that no spatial autocorrelation is found for the residuals (Moran's Index=0.022 and p-value=0.618). Most p-values on the local Moran's I test of the model residuals are less than 0.05, meaning that residuals are not locally correlated (Figure 2-9). Only one location with a low residual value showed slight correlation with surrounding lows.

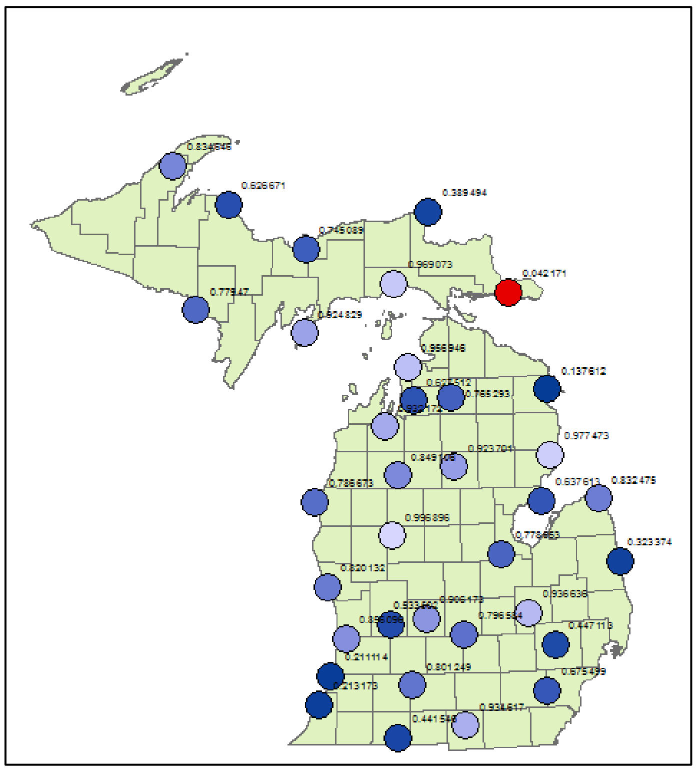


Figure 2-9 p-values of model residuals by the Anselin Local Moran's I

The Hellman exponent estimated by the developed regression model is applied to scale up a measured wind speed profile from a lower to a higher elevation at a place where the measured wind profile is also available at the higher elevation. Due to the lack of qualified measured wind speed profiles that have complete records of hourly wind speed data for a whole year at multiple elevations, only two cases are studied from the anemometer data measured by Michigan State University's wind project [48].

The probability distribution of hourly wind speed for a whole year in the Berrien and Tuscola sites in Michigan shows that applying the optimal Hellman exponent in the calculation of the power law can scale up the ground wind speed profile very approximately to the real wind speed profile measured at a higher elevation (Figure 2-10).

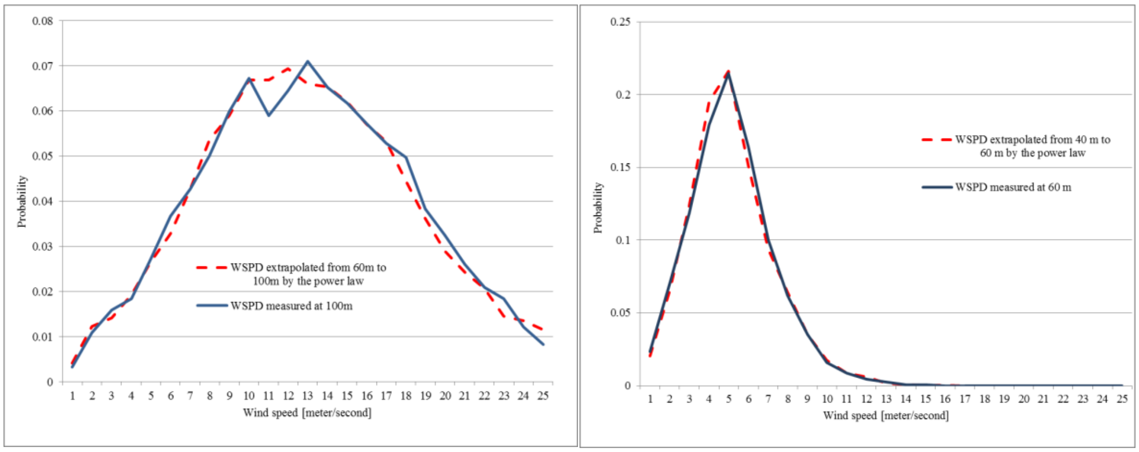


Figure 2-10 Wind speed profile2 from measured and extrapolated dataset2 at Berrien (left) and Tuscola (right) counties

2-4-3. Geostatistical analysis for horizontal estimation of wind speed

Model building

The distribution of hourly wind speed at hub height can be substituted by an approximated probability function (see details in Appendix A). The Weibull distribution can meet the criteria of accuracy and simplicity if suitable parameters, including the scale and the shape parameters, are well decided. Since the scale parameter of the Weibull distribution is basically determined by the average wind speed (available from wind map or ground wind speed extrapolation), attention should be paid to the spatial variation of the shape parameter. The shape parameter at weather stations varies from 1.52 to 1.93, with an average of 1.74, across the study area. Generally, the values are normally distributed, indicating that a transformation of data is not required to produce confidence intervals appropriate for prediction and probability. While the data set of the shape parameter is plotted on a 3-D coordinate system that has locations on an X-Y plane and parameter values on a Z axis, an insignificantly U-shaped trend in the data appears both on the east-west and the north-south planes. Therefore, a second-order polynomial global trend of the studied data could be considered for the purpose of cautiousness or the removal of the global trend can be ignored without affecting the accuracy of kriging.

Based on the characteristics of the shape parameter data, the ordinary kriging method is first applied without the transformation of sampled data and the removal of the global trend. The semivariogram modeling shows the optimized model parameters using cross validation performance. The kriging range considered to best depict the autocorrelation of spatial autocorrelation of the shape parameter is 285 km, which is roughly equal to the distance in the east-west direction across the Lower Peninsula of Michigan.

The inter/extrapolation methods were assessed according to the performance of prediction errors. The cross validation results of the four methods (Table 2-7) indicate that ordinary kriging is best in terms of mean and root mean square. The ordinary kriging model that performed best in predicting the variable of the shape parameter can be further supported by a standardized root-mean-square close of 1.02.

Table 2-7 Prediction errors using cross validation for geostatistical methods

Method	Ordinary Kriging	Universal Kriging	Simple Kriging
Mean of prediction errors	-0.00005	0.02259	0.00345
Root mean square of prediction errors	0.0813	0.1568	0.0831
Standardized root mean square	1.02	1.06	1.05

The predicted shape parameter (Figure 2-11) has smaller standard error in the areas where measured weather data is provided (Figure 2-12). For the potential installation of wind farms in the range of 30 km offshore, the predicted standard error is mostly under 0.0765. This means that, at a 95% confidence level, the variation of the predicted shape parameter is less than 10% ((0.0765)(2)/1.7). Energy generation is not very sensitive to variation of the shape parameter. In an example of a potential wind farm location with the average wind speed of 9 meter/second and the predicted shape parameter of 1.7, the difference of energy generation is about ±4%, at a 95% confidence level, due to the possible variation of the shape parameter.

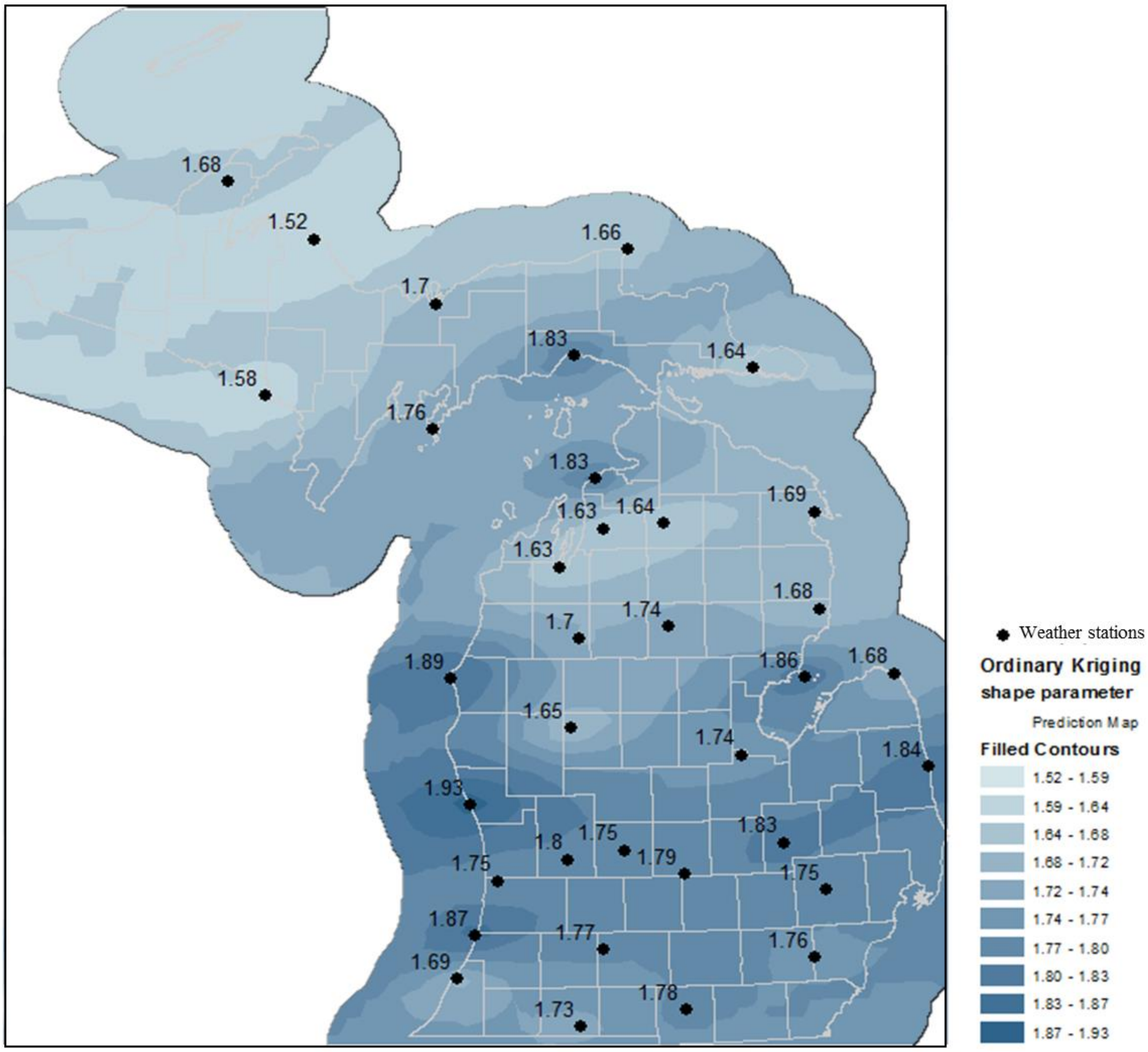


Figure 2-11 Prediction map of the shape parameter K by ordinary kriging method

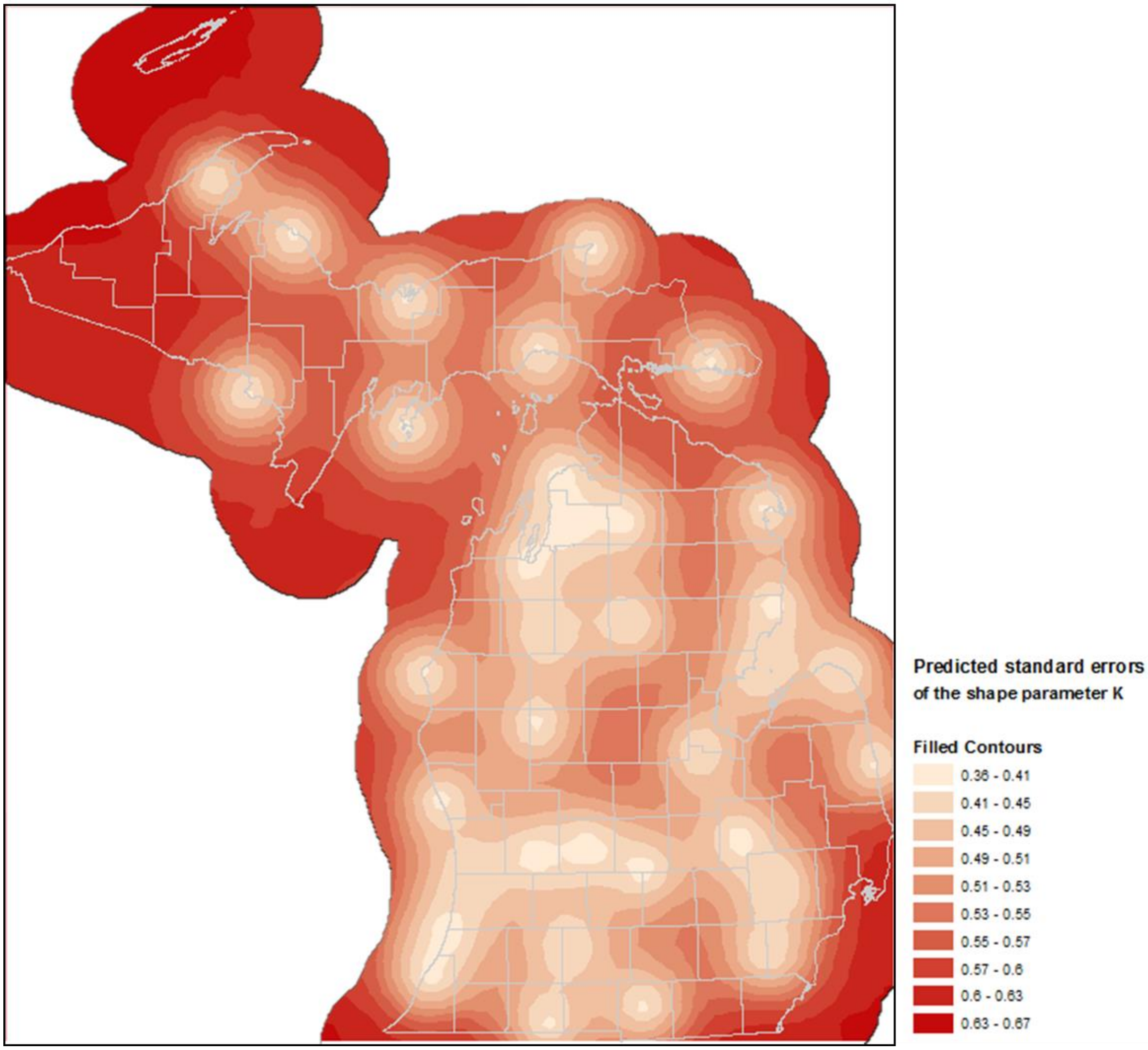


Figure 2-12 Prediction of standard error of the shape parameter K by ordinary kriging

Implication on return for risk unit

Consider a 3MW wind turbine at 100 meter hub height as an example. The variation of energy performance determined by mean wind speed and wind speed distribution is examined for 35 weather stations (Figure 2-13 and Figure 2-14). The dashed line in Figure 2-13 represents best energy performance frontier where energy generation is maximized, given the same level of energy production uncertainty. Three sites, numbered 5, 51 and 89 respectively, are located on the line, implying that the risk to install a wind energy project here can be best compensated compared to locations elsewhere. The result is very similar to the general understanding about wind farm siting, in that wind speed condition in the coastal areas is higher and more stable than that in the inland areas.

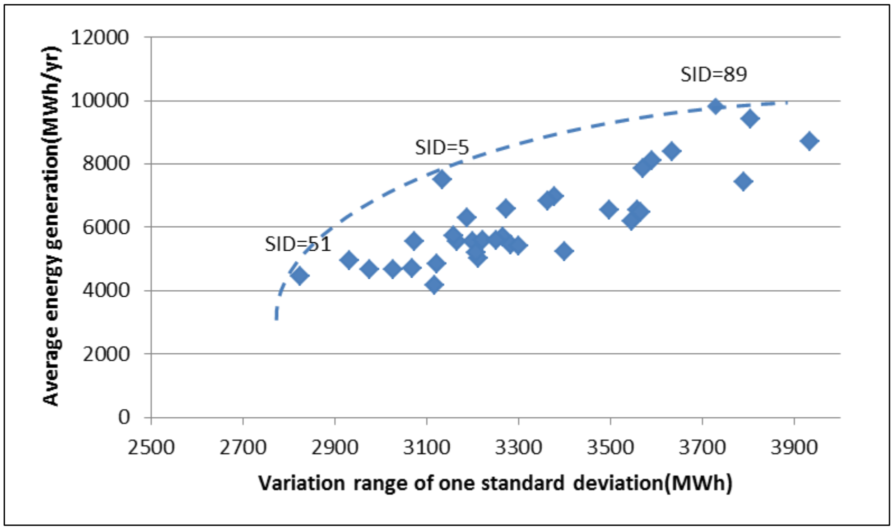


Figure 2-13 Estimated energy return per risk unit frontier

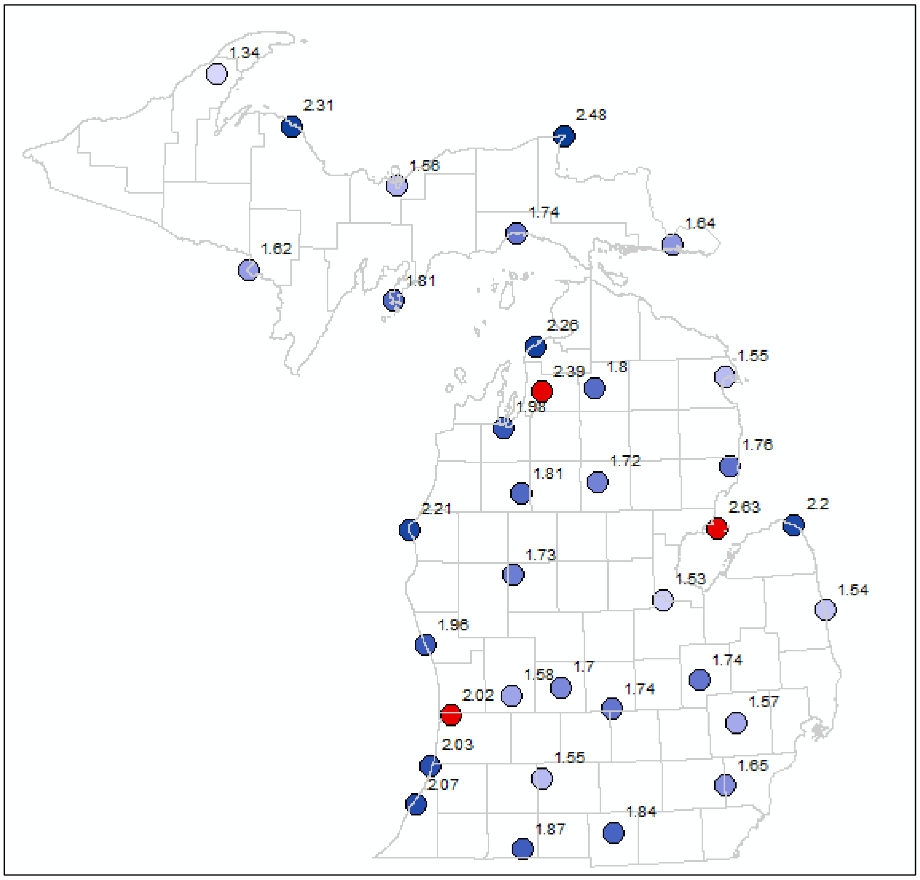


Figure 2-14 Ratio of estimated energy return per risk unit by wind energy generation at 35 weather stations

Energy generation for wind projects in the candidate locations

The measured average wind speed from weather stations close to the four candidate waters is first examined. Wind speed characteristics in SJOM4, MKGM4, LDTM4 and GSLM4 weather stations indicate that Huron county waters have the strongest average wind speed and significant variation based on wind speed standard deviation (Table 2-8). But if the wind condition in an extreme year is examined, Berrien County shows 8.1% more wind speed and Oceana County shows 8.7% less wind speed, compared to the mean of average yearly wind speed. This information provides the reference for sensitivity analysis of wind energy generation (Table 2-8).

Table 2-8 Measured average wind speed for four candidate wind project locations

Mean WSPD at mast height [m/s]	2006	2007	2008	2009	2010	2011	mean	SD	Strong wind speed year	Weak wind speed year
Berrien(SJOM4 station)		3.37	3.74	3.34	3.40	3.43	3.46	0.13	8.1%	-2.5%
Ottawa(MKGM4 station)	5.89	6.16	5.84	5.64	5.59	5.67	5.80	0.18	6.3%	-3.5%
Oceana(LDTM4 station)	3.02	3.54	3.45	3.23	3.25	3.35	3.31	0.16	7.1%	-8.7%
Huron(GSLM4 station)	6.12	5.97	6.09	5.60	6.49	6.21	6.08	0.25	6.7%	-7.8%

The values developed through geostatistical estimation can be used to help determine wind farm locations where energy generation is an important issue of a project's success. Calculation of energy generation is hence accordingly applied for offshore wind farm projects in the four candidate waters, of 5, 10, 15, 20 and 30 km from the coastline. The energy generation of 20 wind farm siting alternatives is measured in terms of the Weibull distribution as a base scenario by using the mean of yearly wind speed and the shape parameter equal to 2. This base scenario is compared to the five other estimation scenarios characterized by major combinations of mean wind speed and shape parameters. The means of yearly wind speed assumed for each estimation scenario range from 90% of the based scenario to the maximum higher percentages observed during the period of 2006-2011. The shape parameter of the Weibull distribution is set to either 2 or the predicted value at each station. For the base scenario, 20-year energy outputs of 100 x 3 MW wind farms range from 2.29 to 2.82 [10^7 MWh] if the estimation method uses mean wind speed and the shape parameter equals 2 (Table 2-9). Compared to the base scenario, energy output estimation is 18% - 24% less if parameters of the Weibull distribution for the purpose of wind energy measurement use 10% less of mean wind speed and the predicted shape parameter. Energy output estimation can average 6% - 11% more compared to base scenario if higher wind speed is adopted from the observed yearly data and the shape parameter of 2 is considered. The significant variation of energy generation estimation demonstrates risk and uncertainty and suggests the requirement of improved wind profile estimation at remote sites.

Table 2-9 Energy generation for twenty siting scenarios by combination of the mean wind speed and the shape parameter

	Berrien					Ottawa					Oceana					Huron				
	5km	10km	15km	20km	30km	5km	10km	15km	20km	30km	5km	10km	15km	20km	30km	5km	10km	15km	20km	30km
Base scenario(k=2)																				
Mean WSPD at 100 m from wind map [m/s]	8.5	8.9	9.1	9.25	9.5	9	9.5	9.75	9.85	10	9	9.3	9.7	9.8	10	8.9	9.2	9.25	9.4	9.5
Shape parameter K	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Annual energy output [MWh] for a Vestas 3MW WT	11438.39	12209.73	12578.86	12848.23	13282.64	12395.70	13282.64	13698.54	13859.63	14095.57	12395.70	12936.57	13616.86	13779.46	14095.57	12209.73	12759.16	12848.23	13111.08	13282.64
energy output for a 300MW OWF by 20 yrs [10^7 MWh]	2.29	2.44	2.52	2.57	2.66	2.48	2.66	2.74	2.77	2.82	2.48	2.59	2.72	2.76	2.82	2.44	2.55	2.57	2.62	2.66
10% mean WSPD decrease(k=2)																				
Mean WSPD [m/s]	7.65	8.01	8.19	8.33	8.55	8.10	8.55	8.78	8.87	9.00	8.10	8.37	8.73	8.82	9.00	8.01	8.28	8.33	8.46	8.55
Shape parameter K	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Annual energy output [MWh] for a Vestas 3MW WT	9665.94	10437.11	10811.77	11097.76	11537.15	10625.40	11537.15	11982.88	12153.39	12395.70	10625.40	11178.57	11887.20	12058.94	12395.70	10437.11	10996.18	11097.76	11358.91	11537.15
energy output for a 300MW OWF by 20 yrs [10^7 MWh]	1.93	2.09	2.16	2.22	2.31	2.13	2.31	2.40	2.43	2.48	2.13	2.24	2.38	2.41	2.48	2.09	2.20	2.22	2.27	2.31
Energy output change in %	-15%	-15%	-14%	-14%	-13%	-14%	-13%	-13%	-12%	-12%	-14%	-14%	-13%	-12%	-12%	-15%	-14%	-14%	-13%	-13%
predicted K																				
Mean WSPD at 100 m from wind map	8.5	8.9	9.1	9.25	9.5	9	9.5	9.75	9.85	10	9	9.3	9.7	9.8	10	8.9	9.2	9.25	9.4	9.5
Shape parameter K from kriging model	1.76	1.76	1.76	1.76	1.78	1.81	1.81	1.82	1.82	1.82	1.81	1.81	1.81	1.81	1.81	1.75	1.74	1.74	1.73	1.73
Annual energy output [MWh] for a Vestas 3MW WT	10316.69	11006.02	11336.79	11578.54	12089.93	11450.40	12267.07	12710.74	12860.31	13079.55	11450.40	11948.09	12575.53	12725.75	13018.10	10949.77	11380.33	11459.47	11631.63	11783.60
energy output for a 300MW OWF by 20 yrs [10^7 MWh]	2.06	2.20	2.27	2.32	2.42	2.29	2.45	2.54	2.57	2.62	2.29	2.39	2.52	2.55	2.60	2.19	2.28	2.29	2.33	2.36
Energy output change in %	-10%	-10%	-10%	-10%	-9%	-8%	-8%	-7%	-7%	-7%	-8%	-8%	-8%	-8%	-8%	-10%	-11%	-11%	-11%	-11%
10% mean WSPD decrease and predicted K																				
Mean WSPD [m/s]	7.65	8.01	8.19	8.33	8.55	8.10	8.55	8.78	8.87	9.00	8.10	8.37	8.73	8.82	9.00	8.01	8.28	8.33	8.46	8.55
Shape parameter K from kriging model	1.76	1.76	1.76	1.76	1.78	1.81	1.81	1.82	1.82	1.82	1.81	1.81	1.81	1.81	1.81	1.75	1.74	1.74	1.73	1.73
Annual energy output [MWh] for a Vestas 3MW WT	8741.66	9425.47	9758.48	10013.05	10509.33	9828.27	10662.41	11123.33	11280.66	11504.41	9828.27	10334.03	10983.39	11141.02	11450.40	9377.91	9821.39	9910.84	10087.86	10244.24
energy output for a 300MW OWF by 20 yrs [10^7 MWh]	1.75	1.89	1.95	2.00	2.10	1.97	2.13	2.22	2.26	2.30	1.97	2.07	2.20	2.23	2.29	1.88	1.96	1.98	2.02	2.05
Energy output change in %	-24%	-23%	-22%	-22%	-21%	-21%	-20%	-19%	-19%	-18%	-21%	-20%	-19%	-19%	-19%	-23%	-23%	-23%	-23%	-23%
Plus energy scenario																				
Mean WSPD [m/s] (faster WSPD)	9.19	9.62	9.84	10.00	10.27	9.57	10.10	10.36	10.47	10.63	9.64	9.96	10.39	10.50	10.71	9.50	9.82	9.87	10.03	10.14
Shape parameter K is given by 2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Annual energy output [MWh] for a Vestas 3MW WT	12741.26	13484.61	13843.66	14095.57	14502.87	13400.98	14249.04	14633.63	14790.02	15010.77	13517.85	14033.32	14676.65	14832.02	15118.14	13282.64	13811.62	13891.48	14141.93	14309.56
energy output for a 300MW OWF by 20 yrs [10^7 MWh]	2.55	2.70	2.77	2.82	2.90	2.68	2.85	2.93	2.96	3.00	2.70	2.81	2.94	2.97	3.02	2.66	2.76	2.78	2.83	2.86
Energy output change in %	11%	10%	10%	10%	9%	8%	7%	7%	7%	6%	9%	8%	8%	8%	7%	9%	8%	8%	8%	8%
Minus energy scenario																				
Mean WSPD [m/s] (slower WSPD)	8.29	8.68	8.87	9.02	9.26	8.69	9.17	9.41	9.51	9.65	8.22	8.49	8.86	8.95	9.13	8.21	8.48	8.53	8.67	8.76
Shape parameter K is given by Kriging model	1.76	1.76	1.76	1.76	1.78	1.81	1.81	1.82	1.82	1.82	1.81	1.81	1.81	1.81	1.81	1.75	1.74	1.74	1.73	1.73
Annual energy output [MWh] for a Vestas 3MW WT	9940.72	10631.36	10955.59	11205.63	11711.51	10912.71	11735.22	12182.11	12340.79	12558.47	10054.95	10553.75	11210.45	11365.25	11668.86	9745.45	10176.11	10263.48	10450.06	10602.35
energy output for a 300MW OWF by 20 yrs [10^7 MWh]	1.99	2.13	2.19	2.24	2.34	2.18	2.35	2.44	2.47	2.51	2.01	2.11	2.24	2.27	2.33	1.95	2.04	2.05	2.09	2.12
Energy output change in %	-13%	-13%	-13%	-13%	-12%	-12%	-12%	-11%	-11%	-11%	-19%	-18%	-18%	-18%	-17%	-20%	-20%	-20%	-20%	-20%

2-5 Discussion

2-5-1. Required modification of the Hellman exponent on wind speed extrapolation

Most historical wind speed data measured at lower heights (i.e., 10m for a standard anemometer at a weather station) are widely used to estimate the wind speed at higher hub heights through the Hellman power law, due to its simplicity and validity. The accuracy of the estimation tends to vary with factors that include location, atmospheric condition, ground roughness and the selection of the Hellman exponent. The accuracy of this calculation is especially important, with the trend of more and more wind turbine installations to harvest the rich wind energy potential at higher elevations. This study demonstrates that various Hellman exponents for different locations are required in order to convert the existing wind data to hub height under the verification of the AWS Truwind wind speed maps. Different from the coefficient of 0.1 commonly used in lakes, oceans and smooth hard ground, the best-matched Hellman exponents are generally larger than the reference coefficient and range from 0.13 to 0.56 based on the prediction of the regression model. Interestingly, the latter number is close to the Hellman exponent usually applied to city areas with high-rise buildings, even though the site (Big Bay) measuring 0.56 was not characterized by an urban landscape.

The reasons for this discrepancy may be rooted in several aspects. First, the physical environment often plays an important role. Although most studied stations are located on the lakeshore and are half- or wholly- surrounded by the water, the Big Bay site are close to irregular dunes as high as 366 meter on the direction of prevailing wind. This may cause the similar impact of high-rise buildings on the estimation of the Hellman exponent. Furthermore, the weather station LDTM4 (the best-matched Hellman exponent is 0.38) can possibly lower the measured wind speed due to the surrounding steep dunes that rise 600 to 800 meters in height over 300 meters of distance. A similar situation may happen at weather station SJOM4 (where the best-matched Hellman exponent is 0.36), where wind speed is affected by the rising dunes as well as the city of Muskegon, with buildings for 15,000 people located to the east of the station.

Besides the micro-terrain features and artificial obstacles on the ground, atmospheric conditions, especially the strong diurnal variations, might be easily overlooked if wind speed averages are examined only based on daily or monthly intervals [32]. When nocturnal surface cooling (stable atmospheric conditions) causes near-zero wind speed near the ground and large vertical gradients above, a large value in the power law exponent is required to extrapolate wind speed. This might explain the high Hellman exponents at SJOM4 and LDTM4 where a high percentage of low hourly wind speeds, equivalent to the extrapolated measured wind speeds lower than 3 m/s at 100 meter hub heights, were observed. These low wind speed data present a diurnal rather than a seasonal pattern. Therefore, it is expected that the larger Hellman exponent values in this research are supported by previous studies and need to reflect the characteristics of atmospheric condition. Wind direction is another factor that could affect the accuracy of the Hellman power law. The prevailing wind direction may decrease wind speed at different levels, depending on the ground friction. The influence of wind direction might be less significant only at the weather station GSLM4, which is basically surrounded by a consistently smooth lake surface.

The adoption of the AWS Truewind wind resource maps as the real mean wind speed at reference height could be problematic, because of the scale issue. Although the validity of the map could be assured by credible data from multiple sources, the meso-scale approach, represented in time and spatial scales, can leave potential questions when applying it to a smaller scale, such as the hourly data and point station in this study. The AWS Truewind map uses six-hour intervals and a horizontal grid of 2.5 km to calculate mean wind speed. This almost likely will decrease the possible variation defined at a finer scale. If the selected weather stations do not represent the wind condition for the regional average, or if the variance of hourly wind speed is very significant, then the bias of matching the extrapolated wind speed from the measured ground wind speed using the large scale wind maps cannot be avoided.

2-5-2. Using a geostatistical method to explore wind speed profiles

Using a geostatistical method and known wind speed data to estimate wind speed profiles at remote sites can provide satisfying results for the purpose of deciding wind farm locations through energy return per risk unit. The introduction of geostatistics overcomes the constraints of data availability in historical wind speed data at an interested location, and utilizes the existing multi-year records from weather stations. Replacing the common value of 2 in the Weibull distribution shape parameter with the predicted value generally decreases 7% - 11% of wind energy generation estimated for the 20 assigned 100 x 3 MW wind farms. Compared to the predicted variation for the shape parameter, which can cause only ±4% uncertainty in energy estimation at a 95% confidence level, arbitrarily choosing a value of 2 for the shape parameter in the Weibull distribution will cause more serious uncertainty in energy output estimation. Moreover, although the amount of energy generation estimated by the modified shape parameter is less, the result approximates energy generation calculated by the measured wind speed at the same location and time period (see Appendix A).

The geostatistical method based on the kriging model still has limitations. The main issue of validity is shown when the method extrapolates data points located out of the range of known data points. In this study, all known weather station data are located on land. The offshore wind farm sites, though close to some land-based weather stations, can only have extrapolated, rather than interpolated, wind speed profiles. The uncertainty of extrapolated wind speed profiles might be exaggerated if the distance of candidate wind farm sites to the closest weather station location is out of the range of the kriging model.

The limit of applying a geostatistical model in broad offshore wind farm siting can be improved by collecting complete year-round wind speed data in waters of the Great Lakes. The current weather stations on lake areas have suffered from severe winter weather and several months of wind speed records are not available, probably due to a frozen anemometer. The deployment of rawin buoys can help provide continuous wind speed measurement, solve the data problem, and improve the accuracy of geostatistical estimation for wind speed profiles.

2-5-3. Applying the Weibull distribution to estimate wind energy potential

The study demonstrates that the estimation of wind energy using the Weibull function or measured wind speed data doesn't cause a significant difference in the amount of calculated wind energy (see the details in Appendix B). Only a 10% difference is revealed, even if a random choice of the shape parameter between 1.2 - 1.6 is made for the Weibull distribution. Applying wrong shape parameters causes less difference than wind speed variation among four studied weather stations in energy generation estimation. Due to the difference of wind speed, the GSLM4 station compared to the LDTM4 can generate more than 27% of the wind energy for one GE 4.1 MW wind turbine generator (Table B-4).

A careful examination indicates that more attention should be paid to comparing wind speed distributions. The Weibull distribution with the shape parameter of 2 only matches the measured hourly wind speed data at the GSLM4; for stations elsewhere, it generally overestimates the frequency of wind speed at which the GE 4.1MW wind turbine generates a lower capacity factor, and underestimates the frequency of wind speeds at which the turbine reaches rated power (100% capacity factor). These sites also underrate the variance of wind speed distributions. For example, the SJOM4 station, with a mean wind speed of 8.05 m/s, has a wind speed variance of 41.2 for the measured dataset, but only 33.9 and 17.7 for the Weibull distribution dataset with shape parameters of 2, and of 1.4, respectively.

Possible impacts on economic feasibility and grid integration may occur if a biased shape parameter is adopted for the Weibull distribution in *ex ante* wind energy estimation. A higher variation of observed wind speeds to the average of the wind speed distribution increases the uncertainty of energy generation prediction. Electricity is hence difficult to sell on the short-term or spot market. Even if the electricity is sold, based on long-term contracts and annual generation amounts, difficulty in integrating wind farms to the grid remains happened.

Furthermore, the dramatic fluctuation of energy output from wind farms will complicate the dispatch management of the limited capacity of transmission lines. Over-generation of wind electricity might be wasted due to the transmission line capacity. Under-generation of wind electricity causes the waste of investment in new transmission line infrastructure. Both situations are inefficient for the management of power grid.

2-6 Conclusions

This study compares estimations of the wind energy potential using measured wind speed data at weather stations with the Weibull distribution. The extrapolation of wind speeds to a hub height is required for weather station data. The Hellman power law is widely used for this purpose. However, the study finds that the best matched exponent is not so easily defined based only upon surface roughness (1/7 or 0.14 is often given to flat areas). The exponent in a flat area can be even as large as 0.38, possibly affected by physical, environmental, and atmospheric conditions.

This study develops a regression model to estimate the most suitable Hellman exponent for each weather station by selecting three explanatory variables, including ground level wind speed, ground roughness and temperature. Although the lack of weather station data on lake waters impacts its application in offshore conditions, the offshore wind projects close to shore still benefit from the estimation method.

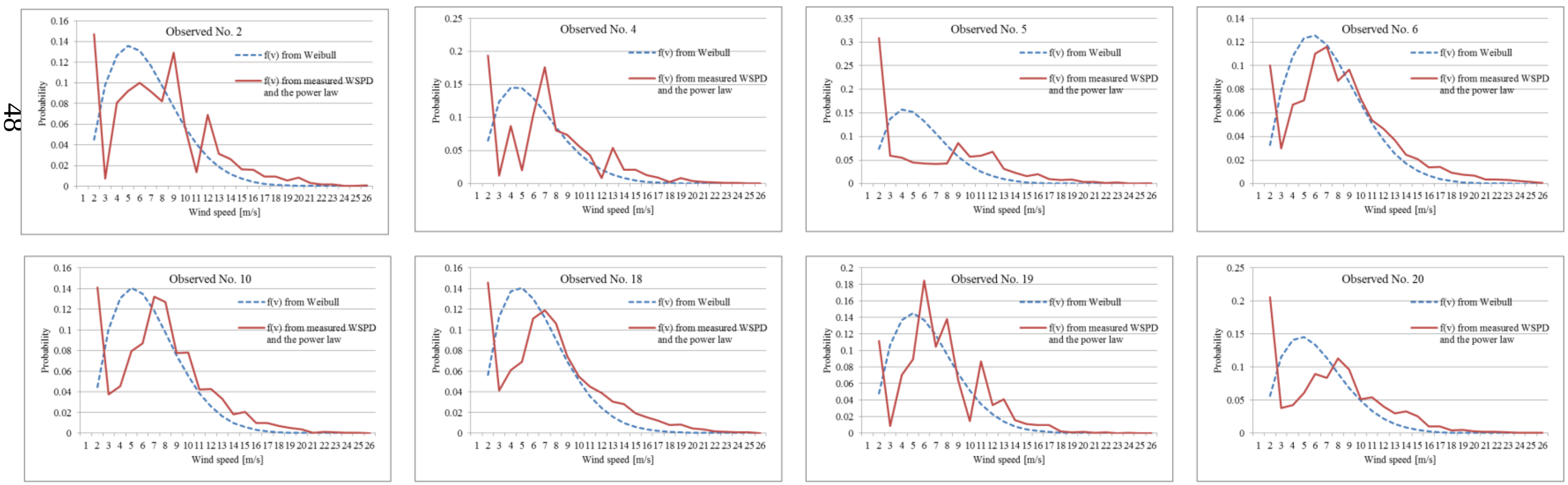
Using the Weibull distribution is another convenient way to evaluate wind energy potential. Applying the Weibull distribution with suitable shape parameters decreases the uncertainty and inaccuracy of wind speed profiles and wind energy generation estimations. Although the selection of a shape parameter with a value of 2 for the Weibull distribution has proven validity in some locations, including one of the studied stations (GSLM4), the remainder of the studied stations using the same approach underestimates the variance of wind speed distributions. Instead, the best matched shape parameters to measured wind data range from 1.5 to 1.8 depending on the wind characteristics of each location.

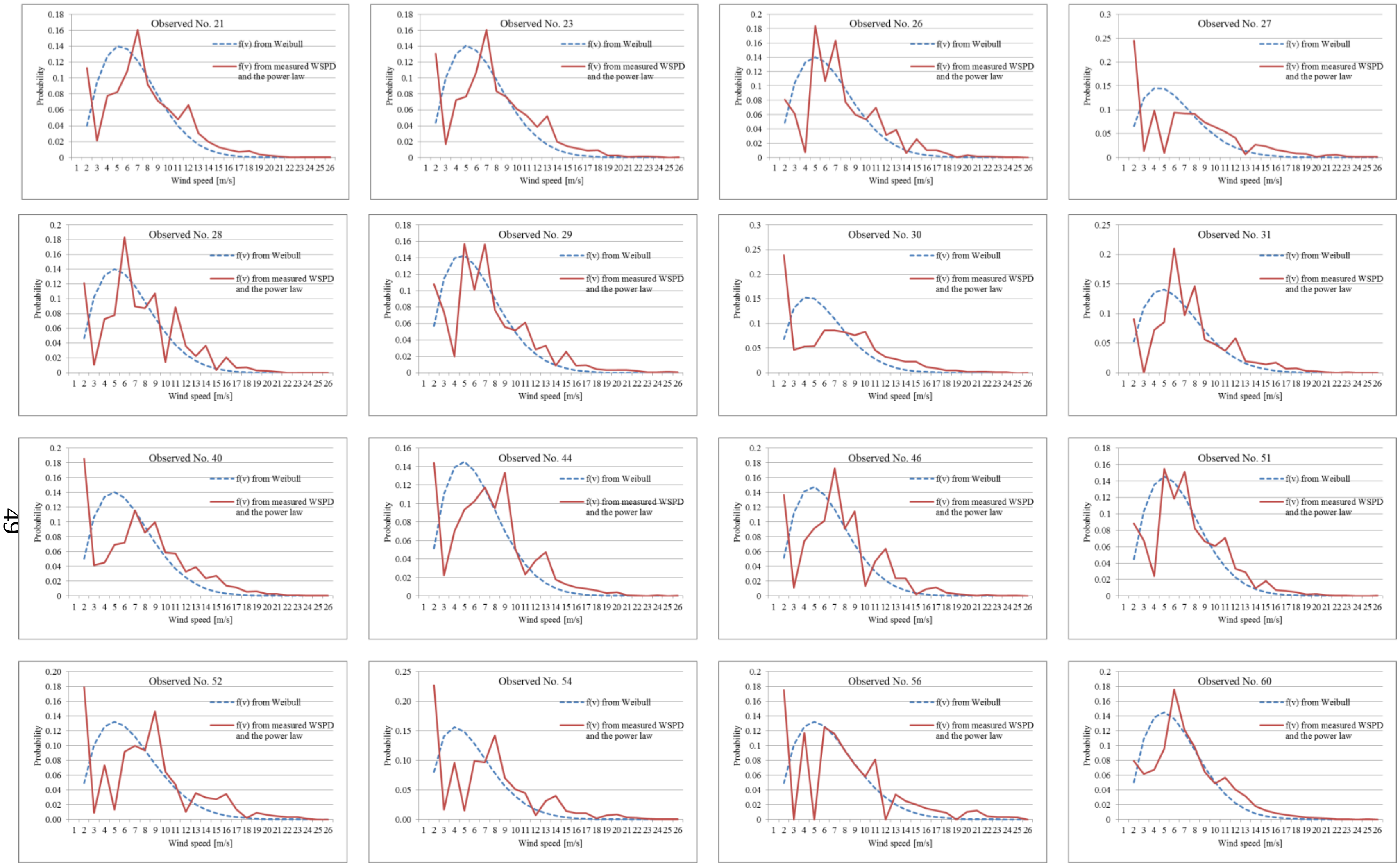
The suitable shape parameter at each weather station is put into the developed geostatistical model to interpolate the values at remote sites. The cross validation of the model proves robust results in the areas with interest. However, the model is still restricted for broad application due to the available data from the offshore lake locations. The model that extrapolates the shape parameter for offshore areas based on year-round wind speed data recorded offshore is expected to improve its certainty of prediction.

Appendix A: Comparison of wind speed profiles from the Weibull distribution and extrapolated weather station data

Wind speed measured at 35 sampled weather stations are scaled up to represent wind speed profiles at hub height by the power law and the suitable Hellman exponent, which is estimated by the regression model developed in this study. Each wind profile is compared to an approximate Weibull distribution.

The results demonstrate that the Weibull distribution can adequately represent the trend of wind profiles extrapolated from weather station wind data. In some locations (observed No. 89, 92, 98, 100, and 102), an accurate representation of wind speed profiles can be seen. For locations elsewhere, measurement errors probably made by a frozen anemometer or recording equipment cause unusual peaks and valleys of frequencies at some wind speed intervals.




Observed No. 21
Observed No. 23
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Observed No. 28
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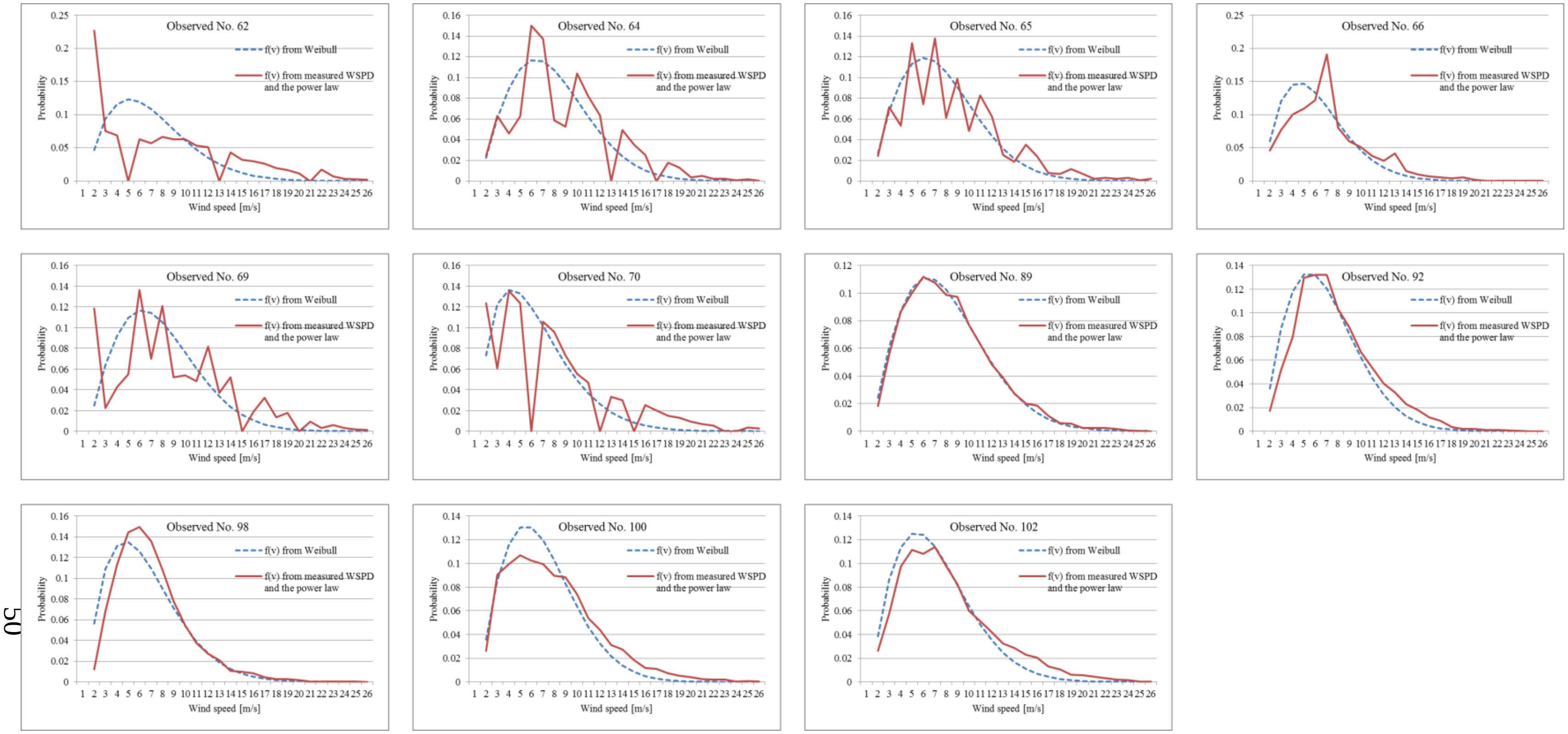
Observed No. 44
Observed No. 46
Observed No. 51
Observed No. 52
Observed No. 54
Observed No. 56
Observed No. 60
f(v) from Weibull
f(v) from measured WSPD and the power law
Probability
Wind speed [m/s]


Observed No. 62
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Observed No. 66
Observed No. 69
Observed No. 70
Observed No. 89
Observed No. 92
Observed No. 98
Observed No. 100
Observed No. 102
f(v) from Weibull
f(v) from measured WSPD and the power law
Probability
Wind speed [m/s]

Appendix B: Comparison of Measured and Statistically-estimated Wind Energy

The best shape parameter of the Weibull distribution is expected to minimize the difference of hourly wind speed distribution compared to station measurement. To evaluate the fit of different values of the shape parameter, several values are tested between k=2 (the Rayleigh distribution, a special case of the Weibull distribution) and k=1 (the exponential distribution). The energy generation from one GE 4.1MW wind turbine is thus calculated at 100m hub height as an index of verification. The index is compared between two scenarios: the wind speed probability dataset using a Weibull function and the real station measurement.

Based on these procedures, a validated Weibull distribution with the best-fit shape parameter can be generated and then applied to calculate wind energy potential in nearby studied areas. The method is very helpful and more accurate in energy generation measurement when mast-measured hourly wind speed distributions are not available.

Data and method

Four land-based weather stations maintained by NOAA (SJOM4, MKGM4, LDTM4 and GSLM4) are selected to investigate the wind speed distribution near four possible development areas of offshore wind farms. As shown in Table B-1, hourly wind speed data measured between 2006 and 2011 at 10 or 24 meter height above site elevation are collected and categorized into annual datasets.

Table B-1 Characteristics of weather stations near studied areas

	Location	Anemometer above site elevation (m)	Dataset (year)	Location	Mean wind speed at 100 m at weather station by AWS Truewind (m/s)
SJOM4	Berrien	10.1	2008, 2011	Close to St. Joseph city at lakeshore	8.0-8.5
MKGM4	Muskegon	24.4	2006-2011	Close to Muskegon city at lakeshore	8.5-9.0
LDTM4	Mason	NA	2011	Surrounded by residential houses on the lakeshore	8.0-8.5
GSLM4	Arenac	24.7	2011	Fixed station on the lake	8.5-9.0

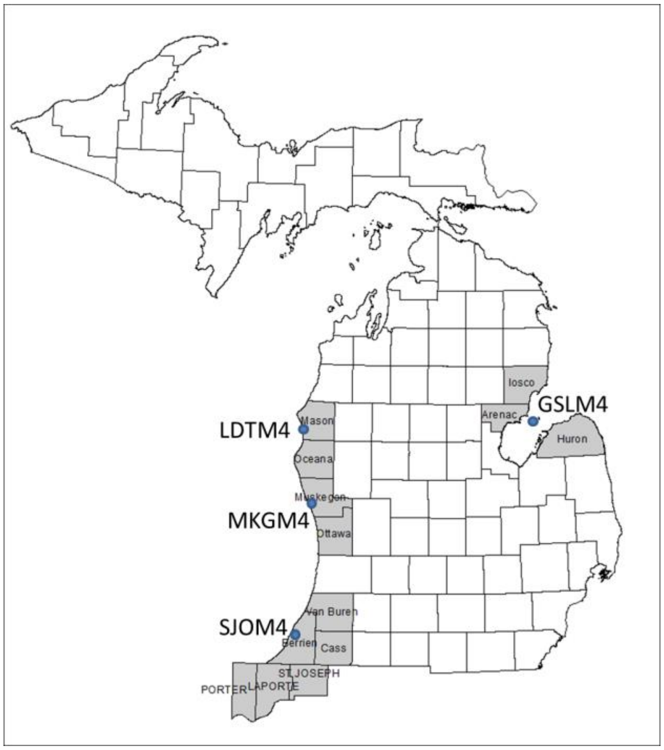


Figure B-1 Maps of the four studied weather stations: SJOM4, MKGM4, LDTM4 and GSLM4

These land-based weather stations are more advantageous than buoy stations, because of the relatively complete hourly wind speed data for a year or for multiple years. The hourly wind speed data is either calculated by the original measurement or by averaging 10 min interval data (SJOM4 only). All datasets representing one-year-long hourly wind speed data contain more than 93% of the 8760 hours of a year. Moreover, the stations are located near the lakeshore and very close to the studied areas of offshore wind farms, and a better extrapolation for wind speed distribution at farther offshore wind farm locations in the same area can be expected.

Results

The various values of the Hellman exponent are tested to express the true effect of wind shear and roughness of surface. As shown in Table B-2, the commonly used Hellman exponent (0.2) for a plane surface and a height above 40 meters does not lead to a good prediction of mean hourly wind speed at the location of Weather Station SJOM4 at a hub height of 100 meters. The percentage difference of mean wind speed to AWS Truewind estimation can be as high as 30%, even though the dataset is examined for two different years ('08 and '11). Instead, using the Hellman exponent of 0.36 creates a more comparatively stable extrapolation of mean wind speed among selected annual datasets at this location, where mean wind speed based on AWS Truewind wind map is in 8.0 - 8.5 m/s range.

Table B-2 Mean hourly wind speed extrapolated by various Hellman exponents to 100 meter hub height at weather station SJOM4, Michigan

Dataset No.	Weather station	Data year	Hellman exponent to transfer wind speed at hub height	Mean wind speed at hub height	difference to AWS Truewind estimation	Recorded number data points of hourly average wind speed
D1	SJOM4	2008	0.2	5.86	-28.97%	8106
D2	SJOM4	2008	0.35	8.27	0.24%	8106
D3	SJOM4	2008	0.36	8.46	2.55%	8106
D4	SJOM4	2008	0.37	8.65	4.85%	8106
D5	SJOM4	2011	0.2	5.58	-32.36%	8600
D6	SJOM4	2011	0.35	7.87	-4.61%	8600
D7	SJOM4	2011	0.36	8.05	-2.42%	8600
D8	SJOM4	2011	0.37	8.24	-0.12%	8600

The best-fit Hellman exponent was then applied to a multi-year wind speed dataset. Limited by the accessibility and completeness of measured data from each weather station, hourly wind speed data are more suitable for comparison only at MKGM4. That station had recorded at least 93% (8177 of 8760) of hourly wind speed data from 2006 to 2011 (Table B-3). Meanwhile, the mean wind speed extrapolated to 100 meter hub height through a value of 0.3 for the Hellman exponent generally matches the mean wind speed calculation by AWS Truewind. All the wind shear extrapolation methods compared to AWS Truewind data demonstrate a difference of less than 8%. Among the interannual datasets, D14 (2011) has less variability. Therefore, it is selected as the representative year for hourly wind speed data at this location and stations elsewhere in the following analyses.

Table B-3 Mean hourly wind speed extrapolated by best-fit Hellman exponents to 100 meter hub height for multi-year dataset

Dataset No.	Weather station	Data year	Hellman exponent to transfer wind speed at turbine height	Mean wind speed	Percentage difference of WSPED compared to AWS Truewind estimation	Recorded number data points of hourly average wind speed
D9	MKGM4	2006	0.3	8.99	+2.74%	8177
D10	MKGM4	2007	0.3	9.41	+7.54%	8515
D11	MKGM4	2008	0.3	8.91	+1.83%	8198
D12	MKGM4	2009	0.3	8.6	-1.71%	8625
D13	MKGM4	2010	0.3	8.54	-2.4%	8206
D14	MKGM4	2011	0.3	8.66	-1.03%	8322

The Weibull distribution is a convenient way to present the wind speed distribution if the shape parameter and the scale parameter can be correctly interpreted. The commonly used shape parameter (k=2) and other possible values (k between 2 and 1) are considered with a scale parameter related to the AWS Truewind mean wind speed, and their corresponding energy generation potentials are compared to energy measured from 2011 weather station data extrapolated to the hub height by a best-fit Hellman exponent. Since energy generation potential is the main interest of this study, the trend of the Weibull distribution for wind speeds is also important in order to reveal the accuracy of wind energy estimation as the correlation to the measured wind speed. Wind energy estimated by the Weibull distribution using the shape parameter of 2 can misrepresent the generation potential, i.e. an 8.7% overestimate in the D17 dataset (Table B-3). However, if the shape parameter were chosen to be 1.2, the difference of energy generation estimation could be significantly reduced to 2.1%. In general, there is no significant tendency showing that using the shape parameter of 2 is better or worse than other values if only estimated energy generation data are provided. Further investigation hence focuses on the comparison of probability curves of hourly wind speeds.

Table B-3 Comparison of energy generation potential from the wind speed distribution between measured data and the Weibull function

Dataset No.	Energy estimated by station measurement (MWh)	Energy estimated by the Weibull factor of the shape parameter of 2	Energy estimated by the Weibull factor of the shape parameter of 1.6	Energy estimated by the Weibull factor of the shape parameter of 1.4	Energy estimated by the Weibull factor of the shape parameter of 1.2
D7	10153	9969	10096	9852	9286
		-1.8%	-0.6%	-3.0%	-8.5%
D14	11148	11553	11297	10814	10005
		3.6%	1.3%	-3.0%	-10.3%
D17	9022	9810	9972	9751	9210
		8.7%	10.5%	8.1%	2.1%
D18	11464	11755	11446	10931	10091
		2.5%	-0.2%	-4.6%	-12.0%

Energy generation estimation of one year is based on one GE 4.1MW wind turbine at 100 meter turbine height

The optimal selection of the shape parameter for the Weibull function is further supported by the demonstration of wind speed distribution. The frequency of hourly wind speeds for one representative year (2011) is shown in Figures B-2 to B-5 using solid lines for SJOM4, MKGM4, LDTM4 and GSLM4, respectively, at 100 m hub height. The wind speed distribution generated by the Weibull function using the shape parameter of 2 is less correlated to the measured wind speed data than the distribution using the shape parameter of 1.4 at SJOM4 and MKGM4 or 1.2 at LDTM2. Only data from GSLM4 shows the Weibull distribution using the shape parameter of 2 being the best fit of the observed wind speed profile. Except at GSLM4, the shape parameter of 2 intensely distorts the estimation of energy generation. Using the shape parameter of 2 underestimates the frequency of wind speeds between 15 m/s to 25 m/s, which are the wind speeds for the rated power of the GE 4.1 MW wind turbine, and overestimates the frequency of wind speeds between 4 m/s to 15 m/s, which are the wind speeds that are below the rated power of the turbine. Moreover, the irregularity of measured wind speed frequency is shown at station MKGM4, where six peak wind speeds are found in the data series with 1 m/s interval (Figure B-3). The irregular peaks of the wind speed frequency may have been caused by a malfunctioning anemometer; these irregular peaks were removed in the analysis.

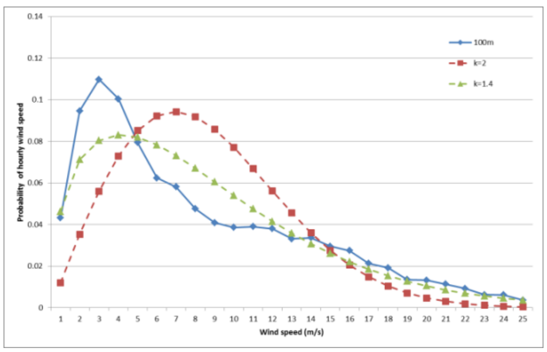


Figure B-2 Probability of hourly wind speed for SJOM4 station

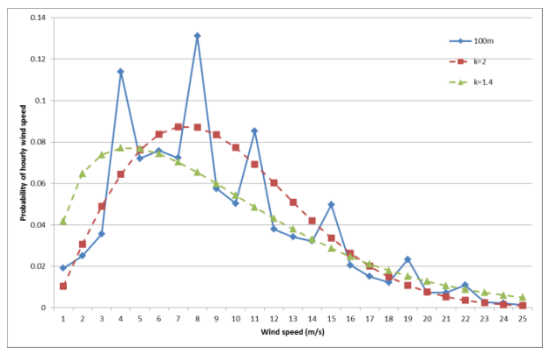


Figure B-3 Probability of hourly wind speed for MKGM4 station

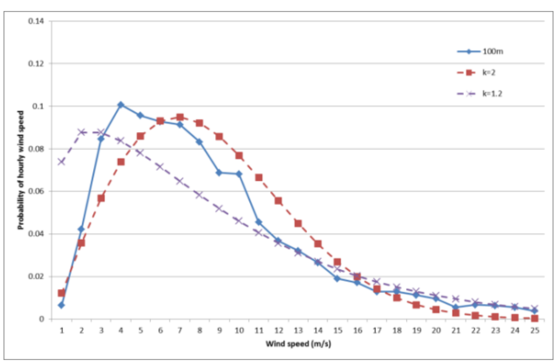


Figure B-4 Probability of hourly wind speed for LDTM4 station

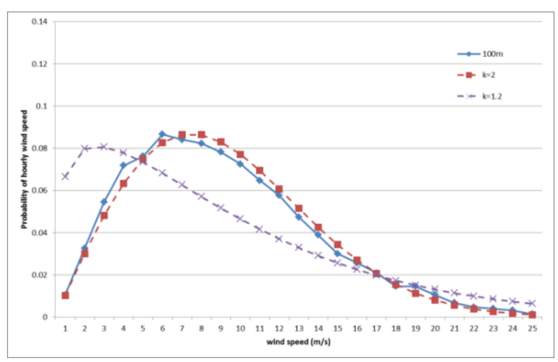


Figure B-5 Probability of hourly wind speed for GSLM4 station

The same procedures used for determining the Hellman exponent, the representative year for the wind speed distribution, and the Weibull shape factor can be applied to other locations. The optimal Hellman exponent that varied with location ranges from 0.38 to 0.25, and does not include the commonly suggested 0.2 (Table B-4). Based on the numbers, the estimation of energy generation potential at 100m hub height from these measured wind speed data generates between 9,022 MWh at LDTM4 and 11,464 MWh at GSLM4. The energy estimation in terms of station data differs from the energy estimated using the Weibull function. The differences are less significant if an optimal shape factor for the Weibull function between 1.2 and 1.4 were selected. The best Weibull energy estimation is found at LDTM4, where only a 2.1% energy estimation difference is present compared to the approach of measured weather data.

Table B-4 Estimation of energy generation potential for four studied locations

Dataset No.	Weather station	Data year	Hellman exponent to transfer wind speed at turbine height	Average wind speed at hub height	Variance of dataset	Energy generation by one 4.1MW GE wind turbine (MWh)	Energy generation estimated by the shape parameter of 2 in Weibull distribution	Energy generation estimated by the optimal shape parameter in Weibull distribution	Optimal shape factor in the Weibull distribution	Recorded number data points of hourly average wind speed
D7	SJOM4	2011	0.36	8.05	41.19	10153	9969	9852	1.4	8624
D14	MKGM4	2011	0.3	8.66	25.20	11148	11553	10814	1.4	8322
D17	LDTM4	2011	0.38	7.99	27.02	9022	9810	9210	1.2	8760
D18	GSLM4	2011	0.25	8.74	24.02	11464	11755	11755	2	8760

Chapter 3
Life Cycle Assessment of Offshore Wind Farms

Abstract

According to previous studies, the life cycle energy intensity of an offshore wind farm (OWF) varies between 0.03 and 0.13 MWh of primary energy for each MWh of wind electricity generated. The variation in these life cycle energy intensity studies, after normalizing for capacity factor and lifespan, is significantly affected by OWF location due to geographic properties, namely water depth and wind speed, which dictate system components. To improve OWF siting, this study investigates how an OWF's distance from shore and geographic location impacts its environmental benefit. A process-based LCA is conducted to compare twenty OWF siting scenarios in the Great Lakes of Michigan for their environmental performance criteria including energy intensity, global warming potential, and acidification potential. Each scenario (four lake locations at five offshore distances) has unique foundation, transmission, installation, and operational requirements based on the respective site characteristics. The results demonstrate that the cumulative environmental burden from an OWF is most significantly affected by 1) water depth, 2) distance from shore, and 3) distance to power grid, in decending order of importance, if all other site relevant variables are held constant. The results also show that when OWFs are sited further offshore, the benefit of increased wind energy generation does not necessarily outweigh the increase in negative environmental impacts. This suggests that siting OWF nearer to shore may result in better environmental performance from a life cycle perspective. Finally, there appears to be a feedback effect in reducing OWF environmental burdens if the OWF systems are recycled, transported in shorter distance or manufactured in a region with a high degree of renewable energy.

Keywords: *Life-cycle Assessment, Offshore wind farm, Wind farm siting,*

3-1 Introduction

Wind power has become one of the fast-growing sources of electricity in the world. The cumulative installed capacity of wind power has globally increased from 10 GW in 1998 to 237 GW in 2011[50]. China, United States, Germany, and Spain are the leading nations in terms of installed wind capacity. They represent 67 percent of total capacity. Although only 3.325 GW of offshore wind energy capacity was operating in the end of 2011 in International Energy Agency (IEA) wind member countries, more countries are planning for offshore wind farm (OWF) developments, including the United States, which approved development of its first offshore wind project and had more than 2GW of capacity in the planning and permitting process by the end of 2010[51]. The gross offshore wind resources of United States is estimated at 4,150 GW, which is roughly four times the supply capacity of current U.S. electric grid[5].

Offshore wind power generation is expected to have the advantage of abundant and consistent wind resources compared to land-based wind power. The higher electricity output is especially advantageous if OWFs have close proximity to major electricity demand centers (coastal populous cities), thus reducing the need to build lengthy transmission lines. Location plays an important role in determining the benefits of OWFs.

Meanwhile, the development of OWFs is encouraged not only by their energy potential but also by environmental benefits to reduce air pollution and greenhouse gas (GHG) emissions relative to other energy sources. Thus, determining how to evaluate the environmental performance with the comparable criteria for different wind farm siting scenarios becomes equally vital to decision makers.

To better demonstrate the environmental impacts of OWFs, life cycle assessment methods are utilized to comprehensively quantify the required resources and energy consumption associated with the generation of one unit of wind energy during the material production, manufacturing, installation, operation, and decommissioning stages. In this study, a process-based life cycle assessment (LCA) is used to explore the environmental impact of OWFs from “cradle to grave”. Since the components and processes needed for OWFs are different from one location to another, their influence on the environmental performance is compared using LCA, and the results are analyzed to decide the best location for OWFs amongst the twenty proposed sites.

3-2 Literature review

This review is organized as follows. Section 1 describes the methodologies and scope of past LCA studies associated with megawatt-level wind power systems. Section 2 reveals the findings especially the environmental performance in the existing body of works. Section 3 discusses the limitation and gaps of the relevant research.

3-2-1. Methodologies and scope of past LCA studies

Criterion for wind power system LCA studies were established to screen for research relevant to this project. Prior work needed to 1) analyze mega-watt scale wind turbines and 2) be published as a scholarly journal article, professional report, dissertation, theses, or be included in LCA software data. The first of the 43 resulting studies (see Appendix D) was published by Devine[52] around 1977 as a theoretical case for a 1.5 MW rated wind turbine system. Both onshore and offshore wind turbines are represented in the remaining studies. There is also diversity in other system characteristics including tower height, lifespan of wind farm components, average wind speed, capacity factor, and offshore wind farm parameters (water depth, distance from shore). The diversity of wind power system LCA studies is summarized in Table 3-1.

Table 3-1 Summary of life cycle assessment studies on a wind farm

Year of study	From 1977 to 2010
Location	32 of 43 studies are located in Europe; most are in Denmark and Germany
Power rating [MW]	From 1 to 6.6 MW for an individual wind turbine
Life time [y]	Most 20 years, some 30 years
Capacity factor [%]	18% to 54%
Analysis type	Process analysis, input-output-based analysis or mixed analysis
Scope as stated	Only 30% of the studies include the life cycle stage of manufacture, transport, construction, grid connection, operation and decommissioning. Almost all studies include manufacture stage.
Rotor diameter [m]	46 to 126.5 meter
Tower height [m]	50 to 124 meter
Average wind speed at hub height [m/s]	6 to 9.2 meter/second
Analyzed environmental impact	Energy intensity, global warming potential, acidification potential and eutrophication

The various specification and diverse assumptions of OWF studies suggest that applying the environmental impact of one case study to another general situation should be done with caution. Further investigation of each system factor is needed to understand their influence on environmental performance measurement.

3-2-2. LCA findings for environmental performance

One common metric of OWF impact is energy intensity, which is defined as the ratio of Cumulative Energy Demand (CED) to wind energy generation over the OWF lifetime. CED states the entire demand for primary energy during the life cycle of an economic good[53]. Another technique for evaluating an energy system is net energy analysis, usually presented by Energy Yield Ratio (EYR) or Energy Return on Investment (EROI). The EYR or EROI used in some studies[54][55] is simply a reciprocal value of primary/fossil fuel energy intensity. If the CED is divided by wind energy generation over an average year or month instead of over its whole lifetime, the result is the time to energy payback for an OWF. Although energy intensity, EROI and energy payback time are slightly different in calculation and definition, the concepts are interchangeable in evaluating the environmental performance related to primary energy consumption from OWFs.

Environmental performance is also frequently measured in terms of global warming potential (GWP), acidification potential (AP), and eutrophication potential. About 63% of the selected studies quantify GWP of OWFs while 35% consider acidification potential. Although not all previous studies consider GWP, AP and eutrophication potential, these results are correlated with primary energy consumption.

The energy intensity resulting from the screened LCA studies ranges from 0.03 to 0.13 [kWh primary energy eq / kWh wind energy]. The variation of energy intensity is mainly attributed to differences in site characteristics, technology, and analysis methodologies.

3-2-2-1. Influence of site-related factors on energy intensity

One of the most significant site-related factors is the average wind speed at hub height, which directly relates to the capacity factor and energy generation of OWFs. Average wind speed is measured by the sum of multiplying different wind speeds and their frequencies. The higher the frequency of wind speed between the cut-in and cut-out wind speed limit of a wind turbine, the greater correlation to potential output of wind energy. This result magnifies the denominator (wind energy generation) of the energy intensity index and hence decreases the energy intensity of OWF.

A similar outcome also occurs by decreasing the numerator of energy intensity as the primary energy consumption changes with the geographic location of manufacture[56][57] and the requirement of transport[58]. The influence of transport on the OWF energy intensity is very straightforward as it depends on the distance between manufacture site and wind farm site and the distance from shore to OWF. Longer transport distances cause more consumption of fossil fuel. The influence of manufacturing countries on energy intensity is more complicated since the efficiency of the power system, the mix of energy supply and production processes all can affect the CED performance. For example, Guezuraga's 2012 study shows that the CED of wind turbine manufacturing is twice as much in China as in Germany[57].

3-2-2-2. Influence of technology on energy intensity

The technology of an OWF is another vital factor that influences its energy intensity. Some key technology parameters include the power rating of a wind turbine; wind turbine efficiency (capacity factor); specification of OWF components; OWF lifetime; and recycling and overhaul approaches. For instance, a higher power rating for a wind turbine can be achieved through the use of larger rotor blades to catch and transform more wind energy into mechanical energy. But larger blades also require more energy and material input to produce. A higher power rating generally requires not only a proportional mass increase in the blades but also in the gearbox, generator, nacelle, tower and foundation[59]. In other words, the power rating of a wind turbine is positively correlated to the mass of all system components as well as the consumption of materials and cumulative energy demand. To understand the energy intensity of a higher rated wind turbine, all factors related to energy consumption and energy generation should be collectively examined.

Technical development also affects the durability and lifetime of the OWF. An extended OWF lifetime is expected to have a lower energy intensity outcome as a result of less primary energy consumption and more wind energy generation. Finally, the impact of recycling and overhaul approaches on OWF energy intensity is determined by component design, avoidance of energy-intense materials, and the energy consumption of recycling processes. Martinez's 2009 study suggested that fuel consumption is one of the most notable impact categories that can be reduced by recycling materials in the decommissioning phase of wind turbine [60]. In the case of the wind turbine tower, recycling reduces 63% of fuel consumption.

3-2-2-3. Influence of methodologies on energy intensity

The third group of variables that influence energy intensity could be attributed to different analysis decisions such as the LCA approach, the scope definition, and the metric definition. Wind farm studies using LCA approaches based on process analysis, economic input-output analysis and mixed approaches can all be found in the literature. Lenzen and Munksgaard (2002) examined the influence of LCA methods on energy intensity using a regression equation and found that economic input-output LCAs have slightly higher reported energy intensities than process-based approaches[59]. But their study included a wide variation of wind power ratings from small wind turbine to utility-scale wind farms. An OWF tends to be larger in both the number and rated power of wind turbines compared to land-based wind farms. Therefore, a specific OWF investigation should be conducted before a comparative interpretation is made.

The LCA scope definition is another decision that can significantly change performance outcomes. Although almost all reviewed LCA studies include the manufacturing stage, only 30% of the studies included all life cycle stages (including transport, construction, grid connection, operation and decommissioning as well as manufacturing). This can lead to significant bias of energy intensity interpretation especially when the manufacturing stage contributes only a small portion of CED to utility-scale OWFs compared to a standalone wind turbine.

Finally, an easily ignored difference in the definition of measurement criteria can cause a deviation of energy intensity result. Take energy payback time (EPB) as an example. The general definition of EPB is expressed as the ratio of CED of all wind farm stages to the yearly generated wind energy valued as primary energy[61]. However, a more precise measurement of EPB will subtract the annual use phase CED from the annual generated primary energy equivalent instead of including the annual CED usage in the whole life cycle CED[62]. This minor variation in calculation can cause huge difference in EPB as fuel consumption of operation and maintenance is significant.

3-2-3. Limitation and gaps in past research

LCA studies are dependent not only on the analysis approaches selected but also on the available data sources. For example, the accuracy of economic input-output LCA depends on how complete and specific the sector matrix table is. It also depends on assumptions made for the operation and maintenance and decommissioning stages. In the case of OWF, the empirical data for these stages is not yet available because OWF developments are not mature enough to collect representative data. Most methodology-centered limitations cannot be easily solved. However, the uncertainty of comparing environmental burdens among different LCA studies can be understood by clearly specifying the scope and measurement criteria.

The limitation from different wind turbine technologies is easier to deal with. Because the technical variation is quantified, several studies have been able to compare the energy intensity or GHG emissions by normalizing/harmonizing the differences in lifetime, capacity factor, system boundary, and GWP for wind power generation[59], [63]. These studies are beneficial for attributional LCA of OWF since the average environmental impact is substantially delineated for the whole system and all components/stages. Very few studies take the consequential LCA approach, which look at the marginal change of inventory and environmental impact in response to decisions (i.e. influence of different siting scenarios on environmental performance)[64].

Site-related factors substantially make conducting a consequential LCA for OWF difficult because changes in system composition are required based on the locational decision. Take a micro-siting situation as an example, in order to increase the capacity factor of a wind turbine, the OWF can be sited farther offshore to harvest higher wind speeds. But this requires a different foundation type due to the deeper water depth. Moreover, the longer distance results in more materials and energy burdens from longer transmission lines and greater electrical line losses during the use phase. If a consequential LCA of different siting scenarios is conducted to fill the study gaps of previous attributional OWF LCAs, the micro-siting of OWFs will hence improve the benefits of the decision due to the informed environmental performance. Variation of site-related factors on the LCA results can also be found in a more macro scale, such as the country of manufacture. Manufacturing wind farm components in different regions determines the fossil fuel consumption and GHG emissions associated with the mix of electricity supply. Since most OWF LCAs are conducted based on electricity data of European countries, this case study is valuable in that it reflects the OWF environmental burdens of offshore wind in the U.S.

3-3 Method and data

3-3-1. A process-based life cycle assessment

Life cycle assessment is a standardized technique that identifies and evaluates the environmental burdens of a product, process or activity across its lifespan from raw material extraction, manufacturing, transport, construction, operation, and end-of-life [65]. Quantifying energy and material usage and environmental releases is thus evaluated not just based on the manufacturing stage, but rather on the entire lifespan (often referred to as "cradle to grave" assessment) [65].

There are two most common LCA approaches: a process-based method developed by the Society of Environmental Toxicology and Chemistry (SETAC) and the US Environmental Protection Agency (EPA) and an economic input-output analysis-based method (EIO-LCA) [65]. Unlike EIO-LCA, which contributes aggregated sales information of each related product sector to the product sector of interest and then calculates the relevant environmental output, a process-based LCA identifies each process flow and calculates its environmental impacts [65]. The latter approach is more appropriate to represent the unique material and energy requirement caused by various OWF siting scenario.

The LCA process is a systematic, phased approach, and consists of four topics: goal definition and scoping, inventory analysis, impact assessment, and interpretation[66]. This LCA follows the principles of ISO 14040-14043 in connection with the four topics. ISO 14040 deals with "principles and framework". ISO 14041 deals with "goal and scope definition and inventory analysis". ISO 14042 deals with "life cycle impact assessment". ISO 14043 deals with "life cycle interpretation". The framework is outlined below:

1. *Goal Definition and Scoping* – Define the purpose and system boundaries that guide life cycle assessment in order to derive environmental impact information from that assessment on how to improve environmental performance. The complexity of choosing system boundaries should hence consider the issues with regard to life stage boundaries, level of detail boundary, the natural ecosystem boundary and the boundaries in space and time.
2. *Inventory Analysis* – Qualitatively and quantitatively list all inputs and outputs of materials, energy and wastes throughout the entire life cycle of a product, process, or activity. The collection and organization of all relevant data is to provide the basis to evaluate environmental burdens or potential opportunities for improvement.
3. *Impact Assessment* – classify and characterize the potential human health and environmental impacts from the use of resources (materials and energy) and environmental releases

suggested by the inventory analysis flow. The key of this stage is to develop the stressor/impact chains. A stressor, a set of materials or processes that cause impact, is organized based on their multiple impacts into a common framework to show concerns such as global warming potential, ozone depletion potential or acidification potential. Further localization and valuation may be also applied in the impact assessment stage. Localization is used to assign higher environmental impacts in certain geographical areas due to the site specificity with the pollution stressors. Valuation is used to give weighting factors to different impact categories according to social value.

4. *Interpretation* – improve environmental benefits or minimize environmental liabilities based on the finding of the preceding phases of the LCA. This stage is therefore used to draw conclusions and make recommendations based on the analysis of results and limitation.

3-3-2. Data collection

This study uses two types of data, background data and foreground data. "The background system delivers energy and materials to the foreground system as aggregated data sets in which individual plants and operations are not identified"[65]. The background data includes the information that demonstrates the upstream materials and processes or that classifies and characterizes the impact. Simapro 7.3.2, Ecoinvent data V2.0, and USLCI data are used to represent the required material, energy and processes for OWFs. Since most ecoinvent data is collected based on European cases, USLCI data is prioritized when the same material/process parameters can be found in both databases in order to show the environmental impact of OWFs in the U.S. Moreover, emission and energy consumption data is measured by two life cycle impact assessment methods. Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2) is adopted for evaluating global warming potential and acidification potential. "TRACI is developed by the US EPA specifically for the US using input parameters consistent with US locations" [67]. The valuation of GWP in TRACI is slightly different from IPCC AR4 [68]. The difference between the GWP valuation methods will be examined in this study. Next, the method used to calculate Cumulative Energy Demand (CED) is based on the method published by Ecoinvent version 2.0 and utilized in the SimaPro 7 software.

The foreground data covers the main processes and material parameters ranging from manufacture, installation, transport, operation and maintenance to end of life. The manufacturing data was obtained from foundation manufacturers and the LCA studies by Vestas[14]. Their V112 3MW offshore wind turbines are used to model the OWF scenarios in this study. Data for installation, and operation and maintenance was taken from the studies on the OWFs, such as the

Anholt offshore wind farm and the Horns Reef wind farm placed in the North Sea [69]. Maintenance requirements are calculated based on the surveyed failure rate of the operational wind farms in Europe [70]. Fuel consumption data for shipping was collected from the construction companies, such as Fred. Olsen Windcarrier. For the end-of-life stage, since no decommissioned OWF data is currently available, assumptions are made for different disposal scenarios.

3-4 System Goal and Scope

3-4-1. Goal

The goal of this study is to enhance decision making of offshore wind farm (OWF) development by evaluating the environmental performance of the OWF life cycle. One of common arguments in favor of wind power generation rather than fossil fuel power generation is the sustainability advantages. Broad environmental assessment that accounts for energy generation as well as environmental performance (i.e. global warming potential, fossil fuel consumption, acidification potential and toxicity and etc.) can evaluate these advantages.

This life cycle assessment, which includes the complete stages from manufacture, installation, transport, operation and maintenance and decommissioning, is able to establish the baseline performance of an entire OWF system. In addition, the individual contribution of each stage, component and process to the total system regarding the environmental loading can be compared. The goal is to provide direction to efforts for pollution prevention, resource conservation, and waste minimization opportunities.

Another goal of this study is to compare the marginal change of environmental burdens in response to different OWF siting scenarios. The consequential LCA for each OWF with different site-related components and processes is used to examine the change in environmental performance by moving wind farms farther offshore. These site-related variables include suitable foundation types, transmission lines as well as corresponding installation and operation and maintenance processes. The result of this consequential LCA is beneficial for OWF micro-siting from the lifetime environmental impact perspective.

3-4-2. Scope

Four proposed areas for OWFs in Great Lakes of Michigan are analyzed to reflect different spatial characteristics with regard to wind speed, water depth and connection to power grid. In each area, five scenarios are separately generated based on the distance from shore, varying from 5km, 10km, 15km, 20km to 30km offshore. Each scenario has the same 100 x Vestas V112 3.0 MW offshore wind turbines, but suitable foundation types and transmission cables vary depending on the site condition.

Since the energy generation from each OWF scenario differs owing to the wind speed variation, the functional unit selected is one kWh wind energy delivered to the grid to maintain an equivalent comparison basis for all scenarios. A 20 year lifetime is assumed for all OWF scenarios. However, the expected lifetime of foundation and cables is 30 years,, therefore only two-third of the lifetime environmental burdens are considered to match the 20 year lifetime of wind turbines. The sourcing of materials and components was based primarily on U.S. data with European data being utilized if the suitable data was not available for the U.S.

The life cycle study for different OWF scenarios contains various components, including nacelle (gearbox, generator and etc.), hub and blades, tower, foundation, transformer substation and collection and transmission cables (submarine cables and land-based cable). As shown in Figure 3-1, each component/subsystem is further assessed by four main life cycle stages, categorized by manufacturing and assembly, installation, operation and maintenance, decommissioning. The required transport between the stages is also integrated into the installation, operation and maintenance, and decommissioning stage. The manufacture stage is defined as a cradle to gate boundary that includes the production of intermediate material from virgin material.

The system boundary of the offshore wind farms is delineated by the second order rule[71], which includes material production, primary energy consumption and material processing, but excludes "capital goods". The “capital goods” here refers to the equipment and facilities used to manufacture the materials for wind turbines.

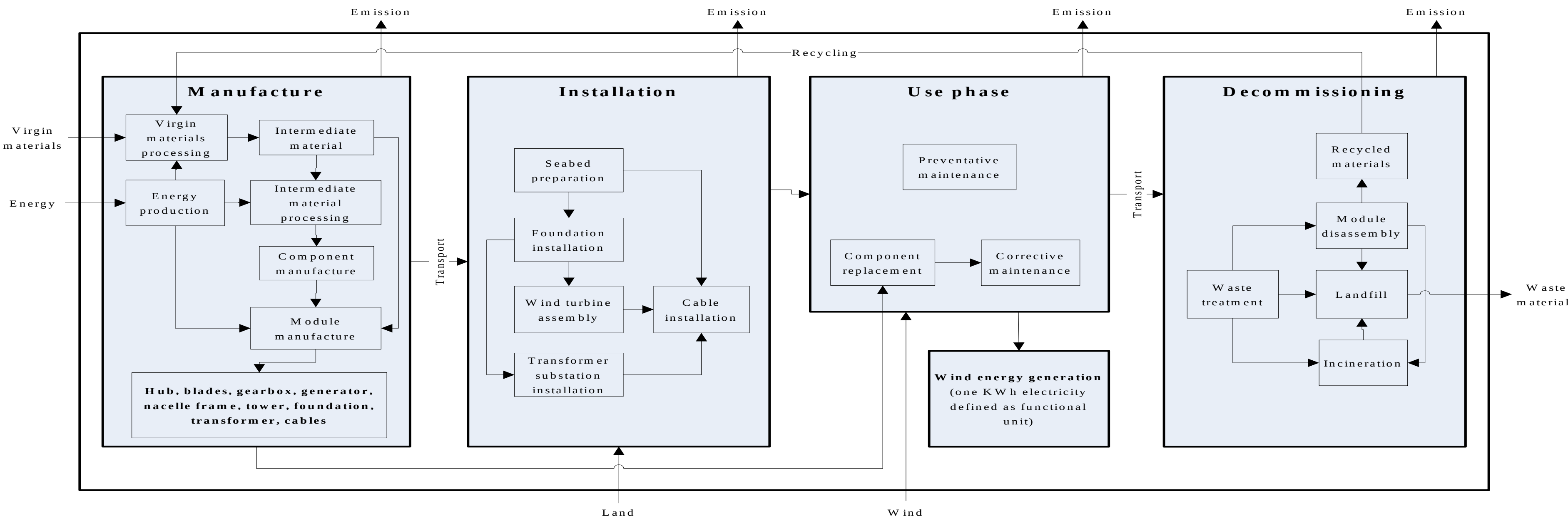


Figure 3-1 LCA scope of an offshore wind farm

3-5 System description and inventory

This section categorizes the system description and inventory of offshore wind farm into four life cycle stages. The first part describes the manufacturing and assembling of OWF components. Next, the transport to erection site and installation of wind turbines are explored. The third part explains the required materials and energy for the operation and maintenance stage. Finally, the decommission stage containing energy consumption and material recycling is presented.

3-5-1. Manufacturing and assembling

The manufacturing of OWF components includes processes ranging from the material extraction, material manufacture, and component fabrication as well as assembly of turbines, towers, cables and transformer substations.

3-5-2-1. Moving parts: 100 x Vestas V112 3MW offshore wind turbines

The Vestas V112 3MW wind turbines are presumed to be installed in the wind farm. The inventory related to the manufacturing of wind turbine components has been derived from Vestas's LCA of V112 3.0 MW turbines[14, p. 112] and Birkeland's research on Havsul 1 offshore wind farm, Norway.[72]

The manufacture of wind turbine moving parts can be decomposed into the manufacture of several important components, including rotor (hub, blades), nacelle (generator, gearbox, low voltage transformer, frame) and others. The main material composition of each component can be seen in Table 3-2. As can be seen, the hub and nacelle consist mainly of steel. In addition, the glass fibre reinforced plastics and synthetic rubber are also essential for the wind turbine.

Several main processes are also considered for the manufacture of each component. The material processing is listed in Table 3-3. When the manufacturing energy consumption data for a specific component were not available, it was then assumed to be equal to the component mass relative to the total mass of wind turbine moving part multiplied by the total energy consumption of wind turbine moving parts manufacturing. The detailed material and process inventory of each component can be found in Appendix C.

Table 3-2 Material use for the moving parts for the 3 MW wind turbine

Part	Material	Mass [t]

Rotor	Hub	Cast iron	23.2
		Aluminum	1.2
	Blades	Glass fibre reinforced plastics	23.4
		Low-alloyed steel	1.23
Nacelle	Bed/frame plate	Cast iron	15.75
	Generator	Low-alloyed steel	6.84
		Chromium steel	0.36
		Copper	4.2
		Silica sand	0.3
	Gearbox	Chromium steel	38.22
		Copper	0.39
		Aluminum	0.39
	LV transformer	Low-alloyed steel	4.95
		Copper	2.25
		Silica sand	0.225
	Nacelle other	Low-alloyed steel	14.745
		Copper	0.252
		Aluminum	3.753
Wind turbine misc		Lubricating oil, propylene, poly ethylene, polyvinylchloride,	17.356
		Gravel	300
		Synthetic rubber	105.5

Table 3-3 Material processing for the manufacture of wind turbine

Material	Processes
Copper	Copper, wire drawing
Aluminum	Aluminum, sheet rolling
Chromium steel	Chromium steel, sheet rolling
Cast iron	Steel, section bar rolling
Steel, low-alloyed	Steel, sheet rolling

3-5-2-2. Tower

The tower is assumed to be 100 meter height. It accounts for 60% of the wind turbine mass excluding the foundation mass; over 90% of the tower mass comes from steel [73]. The steel plates are cut, rolled, and then welded into tower sections.

3-5-2-3. Foundation

Offshore wind turbine foundation can be categorized into several types based on their structural configuration. Gravity-based, monopile, tripod, and floating foundations are commonly used as support structures[74]. With cost being the major consideration, these types are typically used in depths of 0-20 meters, 0 – 30 meters, 30 – 60 meters and above 60 meters, respectively [74]. In this study, the most economical foundation is selected according to water depth for different OWF siting scenarios without accounting for the possible constraints of lakebed geology or weight stress from ice and water movement effects on foundation selection.

Gravity-based foundations

A gravity foundation works by using its weight to prevent the turbine structure from tipping over. The most common foundations use reinforced steel, concrete, sand, stones and iron ore. At the Middelgrund wind farm, the weight of every foundation is 1800 tons including the ballast[75]. The dimension of each foundation is 16.5 m in diameter. When the scour protection is considered, a 6 - 8 m extension is planned around the recessed concrete caisson, leading to a total diameter of about 33 m. The construction sequence of the gravity foundations includes seabed preparation, foundation placement and ballast infilling.

Monopiles

A monopile foundation consists of a single long hollow steel pile, which is up to 6 m in diameter and has a wall thickness up to 150 mm. A transition piece is attached on top of the pile and has a boat landing platform and a deck, which reaches up to about 10 m above the water surface. As an example, each monopile tower foundation planned for the Utgrunden wind farm in the Baltic Sea (20 m depth) has been calculated to contain 490 tons of steel [75]. The installation process for a monopile consists of: (1) the monopile is transported offshore either by floating or on a barge; (2) at the erection site, the monopile is lifted and sunk into water; (3) the monopile is driven into seabed of 20 – 25 m depth by either large impact or vibratory hammers; and (4) the transition piece is fixed to substructure with a high-strength concrete-based material.

Tripods

A tripod foundation for offshore wind turbine consists of a braced Y-frame and three steel piles connecting each end of the frame. The diameter of the tripod's piles, about 3.5 m, is thinner than that of monopile foundations. One of the tripod solutions designed by Offshore Wind Power Systems of Texas LLC has a reported weight of 1654 tons for a seabed depth of 45 m and a 3.6 MW wind turbine[76]. To install the tripod, the frame and the three piles are transported by jack-up barge from the harbor to an erection site. Next, the frame is placed into the desired position, and then the piles are inserted through it. Finally, the piles are driven into the seabed and the tower is fixed on top of the substructure with grout. Since the tripod structure consists of three monopiles and one platform (the volume is equivalent to four monopile foundations), the work time for transportation and installation is assumed to be 25% more for tripod foundation.

Floating foundations

The floating foundation consists of a floating tower ballast submerged with a tensioned cable moored on the seabed substrate. Although this structure is not yet used in commercial wind farms, the first full-scale floating wind turbine demonstration was installed by Statoil off the west coast of Norway. This system is similar to Sway's monopile spar buoy tower where the underwater structures extend more than 100 meters deep. The total foundation steel weight (including tower) of Sway single-tension-leg floating monopile at 120 m depth can reach 1240 tons for 5 MW wind turbines[77]. Meanwhile, a ballast requirement of 2500 tons of gravel is also assumed in the LCA study of a floating offshore wind turbine by Weinzettel et al [78]. Due to the data availability, this study uses LCI from a 5MW floating foundation. Although this might overestimate the environmental impact owing to the issue of system overdesign, the design also assures the wind turbine reliability and safety facing the uncertainty of the water environment.

The construction sequence of the floating foundation starts with driving an anchor pile or suction bucket. A tension cable platform is then floated to the erection site. Finally, anchor cables are installed to connect the base structure to the floating platform[74].

3-5-2-4. Collection and transmission cables

The cables for the collection system and the transmission system in this study are composed of 33 KV and 132 KV HVAC cables, respectively. The 33 KV HVAC cables are used for internal connection between wind turbines and to a high voltage transformer substation located offshore. The composition of the cables is mainly three-core copper conductor that is surrounded by a armor layer of galvanized steel, and is stranded and compacted in XLPE insulating tubes[79]. For the purpose of calculation simplicity and conservative assumption, all collection cables are assumed 630 mm^2 in cross sectional area with a weight of about 29 tones per kilometer [72]. For the transmission cables, the 132 KV HVAC cables are used to transmit electricity from the transformer substation to the power grid. The transmission cables are heavier than collection cables, weighting 88 tones per kilometer, and their composition is similar to collection cables.

3-5-2. Transport to erection site and installation

We assume, that trucks transport the wind turbine components from their production site to the harbor, using a distance of 1000 km, and that the concrete or gravel for ballast, using a distance of 500km. They are then transported from the harbor to the erection site and installed by jack-up boat, which is pulled by tugboat. The work time for transporting and installing one wind turbine is one day for each. This was derived from an Anholt Offshore Wind Farm report by Ramboll[69]. At the end of wind turbine life, the requirement of transport for the components is assumed to be the same as that in the installation stage. This model benefits from the input of more detailed supply chain and logistics information specific to the Great Lakes region.

The upstream processes of transport with regard to usage and maintenance of road and vehicles are calculated in this study. The vehicle impacts are assessed by the proportion of distance transported by a 40 ton truck to the total distance performance of the truck. The usage of road is measured by the unit of meter*year. For example, for a 60 miles/hr truck to transport 100 meter long tower and blades for 1000 kilometers, it will be assumed to occupy 120 meters * 3 (include safety distance between cars) of one lane for 10.3 hrs (1000 kilometer / 60 miles/hr /1.6 km/mile). Based on the assumption, the usage and maintenance of road for component transport are parameterized in the LCA modeling.

The upstream processes of transport with regard to usage and maintenance of road and vehicles are calculated in this study. The vehicle usage impacts associated with material production and manufacturing by a 40 ton truck used for component transport are allocated based on the proportion of distance traveled for OWF transport to the total expected distance traveled over the truck's lifetime. The road maintenance and usage requirements are measured in units of meter*year. For example, for a truck traveling at a speed of 60 miles/hr to transport a 100 meter long tower and blades over a distance of 1000 kilometers, it will be assumed to required 0.11 meter*years of road use (120 meters * 3 [to account for a safe distance between vehicles] * ¼ [i.e. one lane of a four lane road] *10.3 hrs / 8760 hrs/year).

The LCA of foundation installation also measure the impact of land use transformation. The coverage of one foundation and its scour protection ranging from 1195 m^2(gravity based foundation), 291 m^2 (monopile), 763m^2 (tripod) to 22 m^2(floating) are measured for the impact of land use change from natural to artificial water bodies defined by the database of SimaPro7 [53]. The land use impact is characterized by land occupation and land transformation. The land transformation is measured for the land cover change from one type to another. The land occupation measures how long a certain amount of areas has been covered by one land cover type.

3-5-2-1. Foundation installation

The installation process for each foundation is associated with the selection of the foundation type. All four types of studied foundations need to be transported from the production sites to the harbor and then transported to the erection site by ships. For the gravity-based foundation, further preparation of the seabed substrate is needed before foundation setup. As a result of the larger footprint of the installation, more scour protection is required, meaning more rock transportation and dumping. The details and difference of installing various foundation types can be seen in the Table 3-4

Table 3-4 Activity related to installing one wind turbine[69][72]

Foundation type	Activity		Fuel/Equipment	No. of equipment[69]	Work time [hrs][69]	Fuel performance [l/h]	Reference for fuel performance
Gravity based (5km offshore)	Substrate clearance	Transport of excavator	Heavy fuel oil, Barge	1	72	100	Vroon offshore services, 2010
		dredging	Diesel, Excavator	1	72	0.455	Ecoinvent, 2010
		Disposal of substrate materials	Heavy fuel oil, Barge	1	70	100	Vroon offshore services, 2010
	Substrate replacement	Transport of rock	Heavy fuel oil, Vessel	1	8.47	100	Vroon offshore services, 2010
		Dumping of rock	Heavy fuel oil, Vessel	1	72	100	Vroon offshore services, 2010
	Installation	Land transport of foundation	Diesel, truck	1		9.232E6 tkm	
		Transport of foundation	Diesel, Tugboat	2	135	322.6	Clean Air Agency, 1999
		Transport of jack-up	Diesel, Tugboat	2	1.8	322.6	Clean Air Agency, 1999
		Construction of foundation	Heavy fuel oil, Jack-up vessel	1	24	170	Fred. Olsen Windcarrier AS, 2006
	Scour protection	Transport of rock	Heavy fuel oil, Vessel	1	8.47	100	Vroon offshore services, 2010
		Dumping of rock	Heavy fuel oil, vessel	1	72	100	Vroon offshore services, 2010
Monopile (10km offshore)	Driving pile	Transportation of pump/generator	Heavy fuel oil, Barge	1	24	100	Vroon offshore services, 2010
		injection of grout	Diesel, Pump/generator for	1	24	185	Vroon offshore services, 2010
	Installation	Transport of foundation	Gasoline, truck			7.999E5 tkm	

		Transport of foundation	Diesel, Tugboat	2	10.27	322.6	Clean Air Agency, 1999
		Transport of jack-up	Diesel, Tugboat	2	3.6	322.6	Clean Air Agency, 1999
		Construction of foundation	HFO, Jack-up vessel	1	24	170	Fred. Olsen Windcarrier AS, 2006
	Scour protection	Transport of rock	HFO, Vessel	1	5.13	100	Vroon offshore services, 2010
		Dumping of rock	HFO, vessel	1	29	100	Vroon offshore services, 2010
Trpod (15km offshore)	Driving pile	Transport of pump/generator	Heavy fuel oil, Barge	1	24	100	Vroon offshore services, 2010
		injection of grout	Diesel, Pump/generator	1	72	185	Vroon offshore services, 2010
	Installation	Transport of foundation	Gasoline, truck			1.654E6 tkm	
		Transport of foundation	Diesel, Tugboat	2	144	322.6	Clean Air Agency, 1999
		Transport of jack-up	Diesel, Tugboat	2	144	322.6	Clean Air Agency, 1999
		Construction of foundation	HFO, Jack-up vessel	1	72	170	Fred. Olsen Windcarrier AS, 2006
Floating (30km offshore)	Mooring	Transport of suction caission	Gasoline, truck			.500E6 tkm	
		Transport of suction caission	Diesel, Tugboat	1	24	322.6	Clean Air Agency, 1999
		Pump out water	Diesel, Pump/generator	1	24	185	Vroon offshore services, 2010
	Installation	Transport of foundation and ballast	Gasoline, truck			3.505E6 tkm	
		Transport of foundation and ballast	Diesel, Tugboat	2	168	322.6	Clean Air Agency, 1999
		Transport of jack-up	Diesel, Tugboat	2	144	322.6	Clean Air Agency, 1999
		Construction of foundation	HFO, Jack-up vessel	1	24	170	Fred. Olsen Windcarrier AS, 2006

3-5-2-2. Wind turbine installation

The installation activities of the wind turbine include over-land transportation of components from the production sites to the harbor, over-water transportation from the harbor to the erection sites, and component assembly by jack-up vessel and crane. The detailed processes with respective process inputs are provided in the Table 3-5.

Table 3-5 Wind turbine installation process

Activity	Fuel/Equipment	No. of equipment	Work time [hrs]	Fuel performance [l/h]	Reference for fuel performance and notes
Transportation of 3MW wind	Diesel, truck	1		5.926E5 tkm	1000 km land transportation

turbine components					
Transport of jack-up	Diesel, Tugboat	2	48	322.6	Clean Air Agency, 1999
Assembly of wind turbine	Heavy fuel oil, Jack-up vessel	1	24	170	Fred. Olsen Windcarrier AS, 2006

3-5-2-3. Transformer substation installation

The processes needed to install a transformer substation are assumed to be identical to the installation of a wind turbine. The only difference is caused by the larger mass of the transformer substation, leading to more fuel consumption especially during land transportation.

Table 3-6 Transformer substation installation process

Activity	Fuel/Equipment	No. of equipment	Work time [hrs]	Fuel performance [l/h]	Reference for fuel performance and notes
Transportation of components for transformer substation	Diesel, truck	1		6.522E5 tkm	1000 km land transportation
Transport of jack-up	Diesel, Tugboat	2	48	322.6	Clean Air Agency, 1999
Assembly of transformer substation	Heavy fuel oil, Jack-up vessel	1	24	170	Fred. Olsen Windcarrier AS, 2006

3-5-2-4. Cable installation

To analyze the installation of collection and transmission cables for offshore wind farms, four main processes are considered including route clearance, tie-ins and in-field cable installation, shore connection, and shore landing. Each process needs different equipment, which should be mobilized from where they are before beginning on-site operation and demobilized to where they are after finishing the work. For example, during the route clearance, dredging vessels are mobilized to pre-sweep sand waves, leading to a hypothesized mobilization and demobilization time of 4 days.

Table 3-7 Cable installation[80]

Cable section		equipment	Mob/demob [days]	operation	Fuel consumption [l/h]	Notes	Parameters changes with scenarios
Route clearance	Pre-sweep route	Dredging vessel	4	24 hrs/km	100	3 lines over in-field and shore connection sections at 0.5 kn	
	Route clearance	Anchor Handler	4	3.24 hrs/km	100		
In-field operation	Tie-in and installation	Cable lay vessel	16	24 hrs/km	572.9	Include tie-in for each wind turbine	
		Support vessel	4	24 hrs/km	262.5		
		Burial		24 hrs/km	262.5		

		assistance					
	Scour protection	Transportation of rock		0.128 hrs/km	100	OWF is 10 km offshore	yes
		Rock placement vessel		2 hrs/km	100	25 ton rocks/km, not include foundation protection	yes
Shore connection	installation	Cable lay vessel		3.53 hrs/km	572.9	Laying speed 300 m/hr average, 0.5 km cable loading / hr, (12*1.852 km sailing/hr), plus 0.5 days for a tie-in	
	Scour protection	Transportation of rock		0.128 hrs/km	100	OWF is 10 km offshore	yes
		Rock placement vessel		2 hrs/km	100	25 ton rocks/km, not include foundation protection	yes
Shore landing	Installation	Cable lay vessel		2 days	572.9		
		Support vessel		5 days	262.5		
	Shore spread	Winch, bulldozer, backhoe	1	5 days			

3-5-3. Operation and maintenance

For the operation and maintenance of the offshore wind farms, two categories of services are defined in this study. These are scheduled preventative maintenance and unscheduled corrective maintenance. The frequency of preventative maintenance per year is 2.5 days per wind turbine, 7.5 days for a substation, and 14 days for cables[69]. Each day is assumed to include 24 hours of work time. Inputs considered during preventative maintenance include fuel consumption for transport vessels, replacement oil for wind turbines, and other consumable materials. Impacts from gear oil filters and brake pads are assumed to be very small, andhence are excluded in this study. The amount of consumed fuel and oil is measured based on the study of Anholt offshore wind farm[69].

Table 3-8 Maintenance measured in a wind turbine for 20 years

Activity	Fuel/Equipment	No. of equipment	Work time [hrs]	Fuel performance [l/h]	Reference for fuel performance and notes
Preventative maintenance					
Turbine maintenance	Diesel, Vessel	1	1200	262.5	Regular inspection 2.5 days/year for 20 years
Cable maintenance	Diesel, Vessel	1	67.2	150	Regular inspection 14 days/year for 20 years
Substation maintenance	Diesel, Vessel	1	36	262.5	Regular inspection 7.5 days/year for 20 years
Corrective maintenance					
Replacement of heavy component	HFO, jack-up boat	1	11.5	170	Replace one unit of nacelle for every maintenance
Replacement of large	HFO, vessel	1	5.3	170	Replace one unit of gearbox for

component					every maintenance
Replacement of small component (<1 t)	Diesel, Vessel	1	6.95	262.5	
Inspection and repair	Diesel, Vessel	1	2.05	262.5	
	helicopter		8.18		1.066[times/y]*20[y]*0.02[d/times]*24[h/d]*80%

The corrective maintenance impacts are calculated using failure rates to determine the number of failures for wind turbine components. A failure rate of 1.55 [times/year] for a wind turbine in Denmark and Germany has been presented in DOWEC's report (Dutch Offshore Wind Energy Converter)[70]. Since the failures can happen in different parts of the wind turbine system, the responsive maintenance strategies should match the requirement of fixing the problem. The failure is classified into four maintenance strategies according to Rademaker et al.[81], [82]. As shown in the Table 3-9, the annual failure rate is separated into each category, where nacelle and gearbox are selected to represent replacement of heavy and large components respectively. The work time of equipment repair for each type of failure is established in the study by Rademakers et al. by calculating the use of vessel, jack-up and helicopter. These values are multiplied by annual failure rate and 100 turbines in 20 years, leading to the days of transportation and maintenance over the whole wind farm's life span.

Table 3-9 Maintenance strategies based on annual failure rate (based on Rademakers et al. 2003[81])

Maintenance strategies	Required action	Equipment	Failure rate per turbine per year [1/year-turbine]	Replacement of representative part	Work time of equipment for each failure [days]	Days for transportation and maintenance for whole wind farm in 20 years [days]
1	Replacement of heavy component	50%Vessel and 50%Jack-up	0.012	Nacelle	2	48
2	Replacement of large component	50%Vessel and 50%build up internal crane	0.111	Gearbox	0.1	22
3	Replacement of small component (<1 t)	90%Vessel and 10%permanent internal crane	0.362	Not calculated in this study	0.04	29
4	Inspection and repair	20% Vessel and 80% helicopter	1.066	Not calculated in this study	0.02	43

The work time/days for transportation and maintenance represents offshore wind farm scenarios located 30 km from coast. For other wind farm scenarios, every 5km closer to the coast will result in 17% less transport time compared to the 30 km scenario.

3-5-4. Decommissioning

For the decommission stage of the wind farm, all wind turbine components are assumed to be transported by vessels and truck from offshore site to harbor and then to the final treatment location. The gravel for scour protection and seabed replacement is left on site.

Two disposal scenarios are then examined. The all landfill scenario treats the entire OWF waste as inert waste landfill defined by SimaPro7. For the recycling scenario, the detailed disposal flow is shown in Figure 3-2 The recycling scenario specifies how the OWF is distributed over the end-of-life options First, the OWF system is decommissioned and separated into components by assuming the same energy usage as the installation stage. Next, waste treatment is dependent on the material type that is sent to recycling, landfilling, and incineration. At this stage, the component is disassembled by assuming the same energy usage at assembling stage. Metals including steel, cast iron, copper, aluminum and lead are 90% recovered and 10% landfilled; glass fibre components, rubber and plastic are 100% incinerated; the rest material is landfilled.

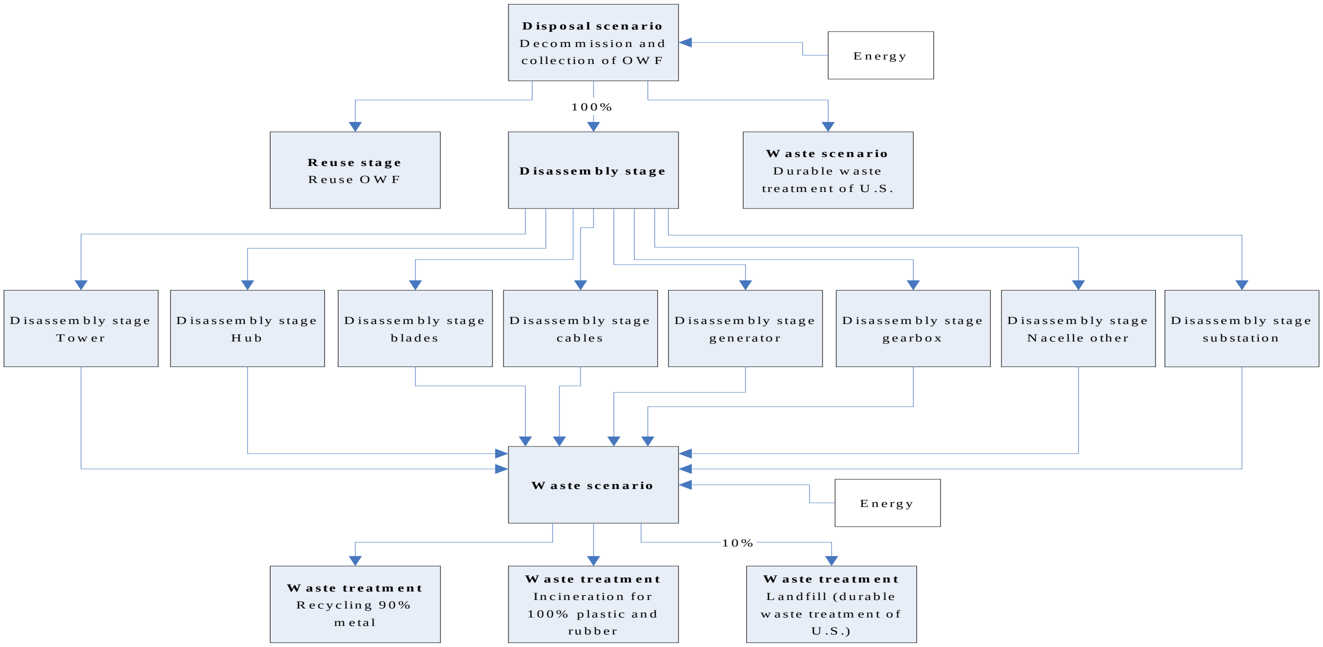


Figure 3-2 The recycling scenario specifies how the OWF is distributed over the end-of-life options

3-6 Results

3-6-1. System characteristics, energy generation and environmental performance for each siting scenario

The characteristics of studied OWF scenarios differs in several aspects, including distance from shore, water depth, foundation type, collection cables, submarine transmission cables, and over-land transmission cable. As can be seen in Table 3-10, siting OWF between 5 km and 30 km offshore in four candidate counties of Michigan has water depth ranging from 15 meter to 140 meter. The significant variation in water depth leads to differences in the most economical foundation type: GBF, monopile, tripod, or floating. The distance from shore and water depth both determine the length of internal cables and submarine cables. The distance of over-land transmission cables for the scenarios is substantially different from one scenario to another due to differences in proximity to the existing grid infrastructure.

Wind energy generation, which is correlated with the average wind speed, increases with the distance from shore for each OWF scenario. The most electricity delivered (1.85E+07 MWh) can be found at the location 30 km from shore in Ottawa County. This scenario has nearly 25% more electricity delivered than the worst scenario (Berrien 5km). The variation of energy generation for OWFs at the same distance offshore but in different counties is more significant than that at different distance offshore but in the same county. This implies that micro-siting OWFs (OWF location within the range of 30 kilometer offshore in a county) potentially have less variation in wind energy estimation.

Environmental performance with regard to GWP, AP and CED for the studied scenarios is most significantly affected by the selection of foundation type. Compare the two scenarios located 5km offshore in Berrien and Oceana County, where gravity based and monopile foundations are chosen respectively; the GBF scenario produces 44% more CO_2 eq, 47% more H^+ eq and consumes 46% more primary energy than the monopile based scenario.

Relative to the influence of foundation type change, the influence of other factors affected by changing distance from shore on the environmental performance is minor. For the scenarios where the same foundation type is adopted such as the Ottawa scenarios that are located 10km to 30km offshore, a 200% increase in offshore distance only results in an increase of 14% more CO_2 eq emissions.

The environmental burden of the scenarios is least sensitive to the variable of over-land cables. Consider two scenarios where foundation type is the same and length of submarine cables are similar: the Huron 10km scenario, which has 100 km of over-land transmission cables has almost the same CO_2 eq. emission compared to the Berrien 10km scenario, which has 3 km of over-land transmission cables (two scenarios are compared by total emission amount not by functional unit).

Table 3-10 System characteristics, energy generation and environmental performance for 20 OWF siting scenarios

	Berrien County					Ottawa County					Oceana County					Huron County				
Distance to offshore	5	10	15	20	30	5	10	15	20	30	5	10	15	20	30	5	10	15	20	30
Water Depth [m]	20	30	40	50	70	25	60	85	100	105	25	50	60	100	140	15	20	35	35	50
Foundation types	GBF	mono pile	tripod	tripod	floati ng	mono pile	floati ng	floati ng	floati ng	floati ng	mono pile	tripod	floati ng	floati ng	floati ng	GBF	mono pile	tripod	tripod	tripod
Internal cables [km]	79.92	80.92	81.92	82.92	84.92	80.42	83.92	86.42	87.92	88.42	80.42	82.92	83.92	87.92	91.92	79.42	79.92	81.42	81.42	82.92
Submarine transmission cable [km]	5	10	15	20	30	5	10	15	20	30	5	10	15	20	30	5	10	15	20	30
Transmission cable on land [km]	3	3	3	3	3	25	25	25	25	25	3	3	3	3	3	100	100	100	100	100
Wind energy generation																				
Delivered Electricity by 100 Vestaas V112-3.0MW wind turbine in 20 years [E+07 MWh]	1.48	1.58	1.62	1.66	1.72	1.63	1.75	1.81	1.83	1.85	1.64	1.71	1.80	1.82	1.85	1.54	1.59	1.60	1.62	1.64
Environmental performance of OWF																				
GWP [E+08 kg CO_2 eq]	6.05	4.41	6.76	7.33	6.57	4.21	5.75	5.96	6.17	6.58	4.20	6.93	5.95	6.16	6.58	6.06	4.41	6.62	6.82	7.77
Acidification [E+08 H+ eq]	1.96	1.49	2.14	2.39	2.47	1.33	1.82	1.99	2.15	2.47	1.33	2.08	1.98	2.15	2.47	1.96	1.49	2.11	2.27	2.72
Cumulative Energy Demand [E+09 MJ , non renewable, fossil]	8.70	6.29	9.54	10.34	9.40	5.98	8.19	8.50	8.81	9.41	5.97	9.75	8.49	8.80	9.41	8.72	6.28	9.33	9.63	10.97
Environmental performance per functional unit																				
GWP per one Kwh wind energy [g CO_2 eq/kWh]	40.85	27.98	41.68	44.29	38.10	25.73	32.88	32.95	33.75	35.51	25.56	40.46	33.06	33.87	35.46	39.43	27.66	41.28	41.97	47.32
Acidification per one Kwh wind energy [moles H+ eq /kWh]	0.013	0.009	0.013	0.014	0.014	0.008	0.010	0.011	0.012	0.013	0.008	0.012	0.011	0.012	0.013	0.013	0.009	0.013	0.014	0.017
CED per one Kwh wind energy [kWh/kWh]	0.163	0.111	0.163	0.174	0.151	0.102	0.130	0.131	0.134	0.141	0.101	0.158	0.131	0.134	0.141	0.157	0.109	0.162	0.165	0.186

3-6-2. The trend of environmental performance for different OWF siting scenarios based on a functional unit

Siting OWF nearer to shore generally results in better environmental performance per unit electricity generated from a life cycle perspective. The reason for this trend is because the increase of negative environmental impact outweighs the increase of wind energy generation when OWFs is sited farther offshore. But two exceptions should be noted: monopile foundations are more favorable in the shallow waters compared to GBF foundations, and floating foundations are more favorable than tripod foundations even though in both cases the wind farms are farther offshore.

The best environmental performance scenario (Oceana 5km) has average energy generation but low environmental loading among twenty studied scenarios. Among 20 siting scenarios, it ranks only the 14th best in electricity delivered, but the best in all environmental impact criteria. Its global warming potential of 25.56 g CO_2 eq/kWh, acidification potential of 0.008 mole H+ eq/kWh and energy intensity of 0.101 kWh none renewable energy eq/kWh are 46%, 51%, and 46% less than the environmentally worst scenario (Huron 30km). However, attention should be paid here for influence of wind speed uncertainty on the environmental performance of each siting scenario. The annual mean wind speed variation can be as high as 17.2% and 15.8% for Oceana County and Huron County respectively (see Chapter 2).

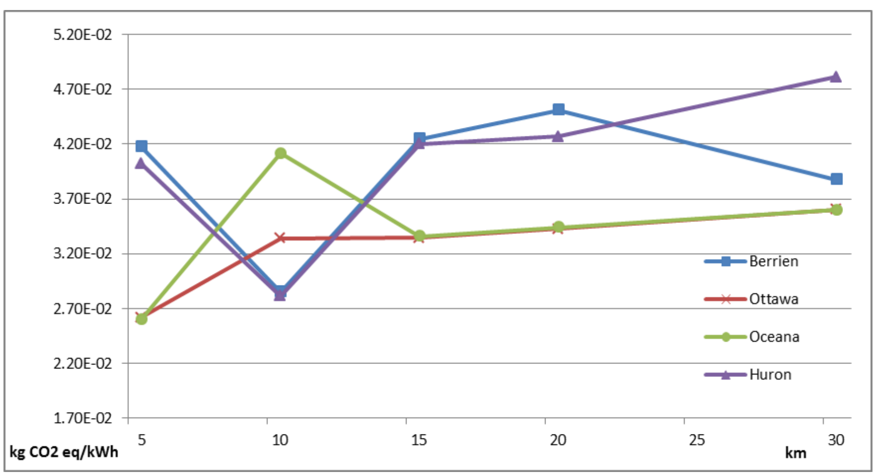


Figure 3-3 GWP per functional unit for different siting scenarios

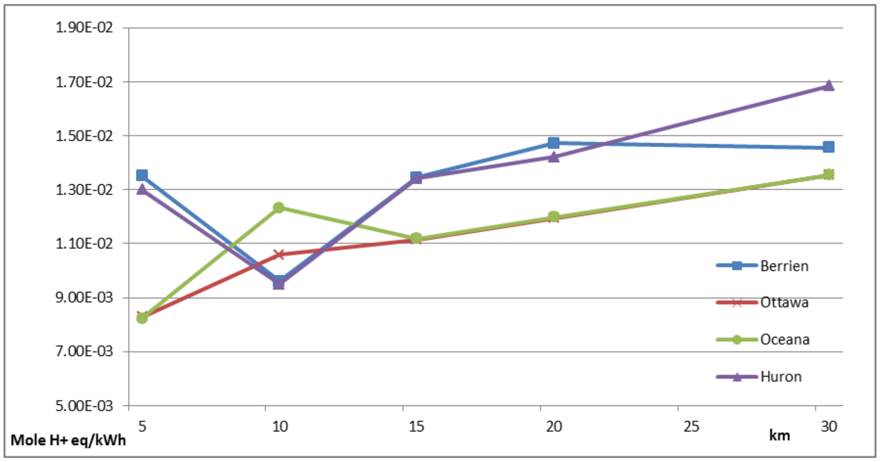


Figure 3-4 Acidification potential per functional unit for different siting scenarios

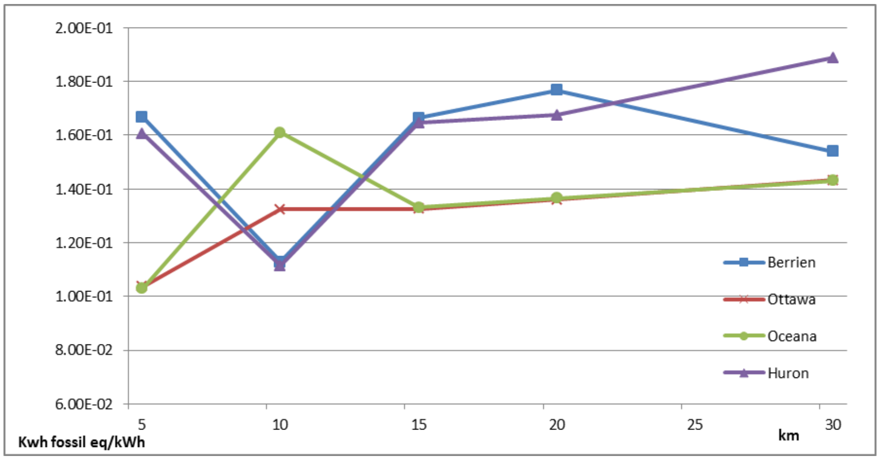


Figure 3-5 Cumulative energy demand per functional unit for different siting scenarios

3-6-3. Comparison of environmental performance among OWF components and processes

Contributions of different life cycle stages to environmental burdens vary from one another according to the composition of OWFs. Take the example of Berrien OWFs as shown in Figure 3-6, manufacturing stage compared to the other stages is responsible for most of the CED ranging from 36% to 63% of total primary energy consumption. Among four main types of OWF foundations, OWFs with gravity based foundation have lower CED proportion from manufacturing stage, but require more transport of heavy mass during installation and decommissioning stages. On the contrary, the CED fraction during the manufacturing stage is highest for the tripod foundation because steel manufacturing consumes more energy and the light-mass foundation compared to GBF requires less energy during installation.

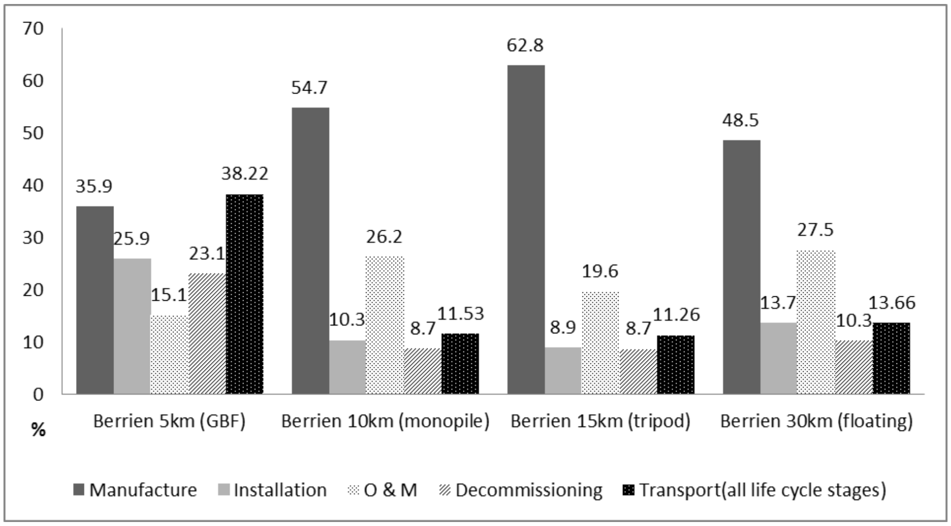


Figure 3-6 CED contribution of different life cycle stages for four typical foundation type scenarios

The CED at manufacturing stage is separated by the OWF components in order to highlight this critical stage. As shown in Figure 3-7, the components contributing the largest portion to the OWF's CED are the foundation and tower along with the miscellaneous category (mainly rubber). For OWF with tripod foundation, more than 85% of CED at manufacturing stage is driven by these three categories.

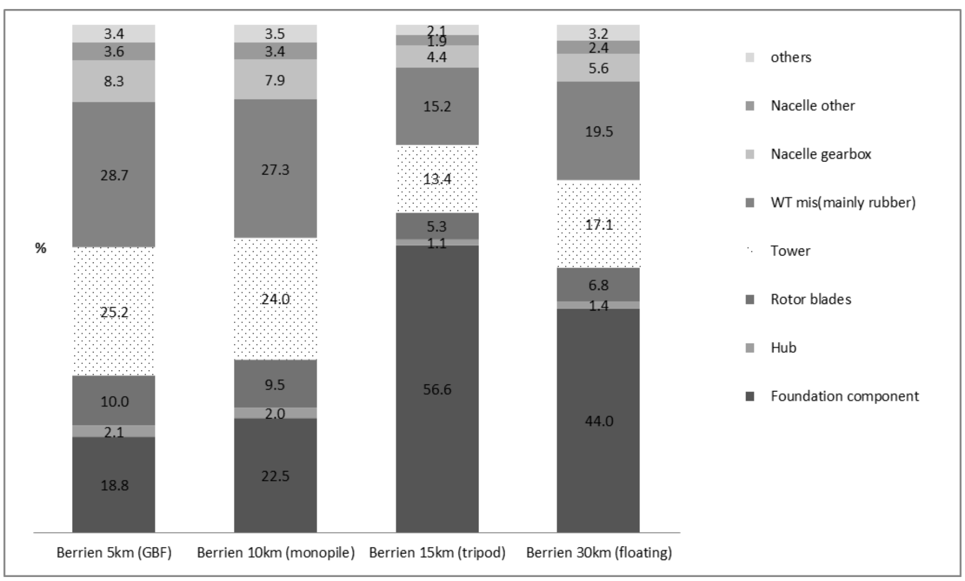


Figure 3-7 CED contribution of OWF component during manufacture stage

3-6-4. Source of environmental burdens

The main factors contributing to greenhouse gas emissions include the consumption of diesel/gasoline for transport, coal burned at power plant and industrial furnace, cement production, and pig iron production. These identified processes cause 54% to 65% of greenhouse gas emissions. The Figure 3-8 shows that fuel consumption for transport during the installation, O&M, and decommission stages is the most significant contributor to greenhouse gas emissions. In the Berrien 5km scenario, fuel consumption for ship transport and truck transport lead to 9% and 31% of greenhouse gas emissions, respectively. Meanwhile, coal consumption for the purpose of power generation and for the production of industrial heat is another significant source of greenhouse gas emissions. Finally, the process of pig iron manufacturing and cement manufacturing collectively generates about 20% of total greenhouse gas emissions.

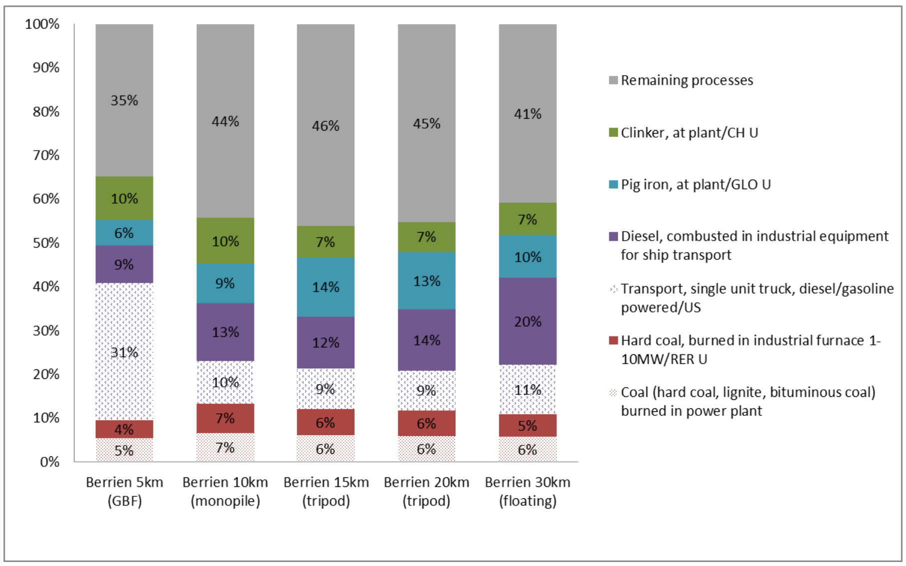


Figure 3-8 Contribution of GWP by processes
The remaining processes stand for the aggregation of processes which has GWP contribution less than 3%

The GWP is identified and characterized by several impact assessment methods, including IPCC 2007 GWP 20a, 100a, 500a, TRACI v2 and TRACI v3 (also called TRACI 2). The results in Figure 3-9 show the greenhouse gas emissions relative to TRACI v3, which is taken as the baseline for comparison to other methods. GWP characterized by IPCC 2007 100a is 1% less than by TRACI v3. The IPCC 2007 500a and TRACI v2 results are also less. The reason for the discrepancy is that IPCC 2007 500a method is calculated over a longer time interval compared to TRACI v3. The impact of CO2 on global warming effect decays with time. On the other hand, the discrepancy of GWP measured by TRACI v2 methods can attribute one of the reasons to incorporating the indirect effect of CO on GWP in TRACI v3. Only small amount of CO is emitted during the OWF life time. CO can reduce the concentration of OH radicals in the atmosphere and further avoids their effect on reducing the lifetime of strong greenhouse gases, such as methane. This is the driving factor that GWP by TRACI v2 is 5% less than by TRACI v3 for the same siting scenario.

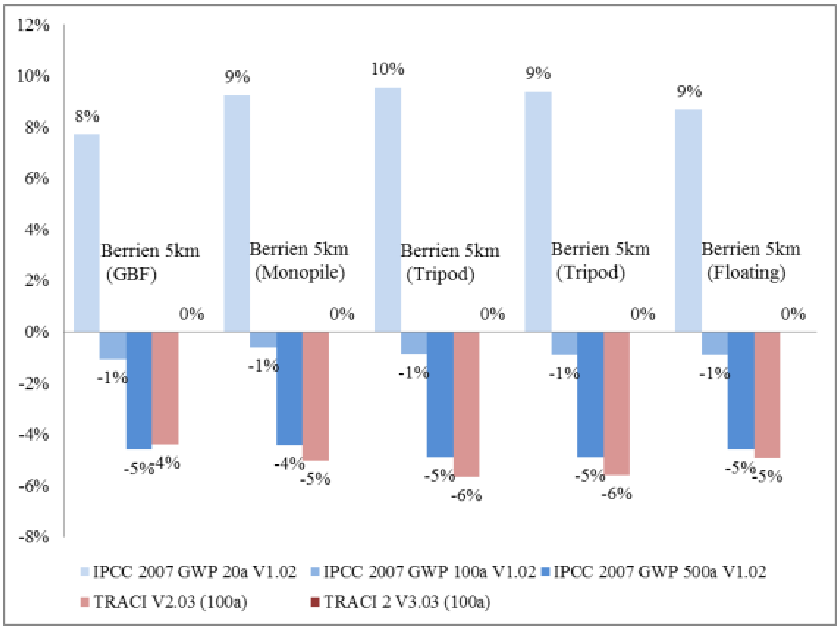


Figure 3-9 Comparison of GWP by five impact assessment approaches

3-6-5. Benefits of recycling WT components in the end-of-life OWF

The twenty siting scenarios are compared using two end-of-life alternatives, landfill and recycling. The scenarios are grouped into four types by the foundation. As seen in Table 3-11, all environmental burdens are improved for three indicators when recycling strategies are adopted for end-of-life management. The most improved siting scenarios are those with tripod foundations. The GWP of the recycling scenarios are 52% less than landfill scenarios for OWFs with tripod foundations. The improvement in AP and CED can reach reduction as much as 33% and 59%, respectively. The reason for significant improvement of environmental performance on these scenarios is that tripod is mostly composed of steel. Recycling steel can thus substantially reduce the material processing of steel decreasing energy consumption and air pollutant emission. However, conclusions made for the benefits of recycling steel based on this simplified modeling should be cautious. Some of the reasons might include (1) what percentage of used steel can be recycled, (2) different energy consumption for virgin and recycled steel production, (3) what percentage of recycled steel had been used for the manufacture of wind turbine components.

Table 3-11 Benefit of recycling for OWFs with different foundations

	GBF	Monopile	Tripod	Floating
GWP	-15%	-30%	-52%	-34%
AP	-13%	-24%	-33%	-22%
CED	-20%	-41%	-59%	-40%

3-7 Discussion

Life cycle environmental impacts of OWFs are jointly determined by site-related factors as well as technical factors, which are not site-specific. In this section, the influence of site-related factors on environmental performance of OWFs is discussed first. Next, the influence of macro-siting factors on environmental performance is discussed. Since the environmental performance of OWFs is significantly influenced by the technical factors, they are discussed in the third section. In the final section, the results of this study are compared to the past LCA studies on wind farms.

3-7-1. Three site-related factors (distance to power grid, water depth and distance from shore) have different impacts on the environmental performance of OWFs

Micro-siting OWFs is defined as a series of processes for refining OWF site selection within a small geographic scale in order to best achieve the project objectives. In this study, the objectives, energy generation and environmental performance, are analyzed for a series of OWF siting scenarios. These two objectives are affected by three site-related factors: (1) distance from shore, (2) water depth and (3) distance to power grid. Siting OWFs farther from shore can result in harvesting more wind energy from higher wind speed, but also consumes more resources due to longer transmission cables and transport requirement. In addition, locations farther from shore tend to be deeper, and thus require alternative foundation types. Finally, the distance to power grid determines the length of land-based transmission cables and hence changes the environmental impact.

Thus, different wind farm locations are characterized by the interdependence of three site-related factors, which can alter the environmental performance of OWF per kWh wind energy generated. OWFs located in shallow water depth, close to shore, and a short distance from power grid have a more favorable environmental performance per functional unit. When

OWF location is located a greater distance from shore, the environmental performance per functional unit becomes worse. This suggests that the benefit of increased wind speed is offset by the increase in environmental burden.

Prioritizing site selection characteristics based on the comparative importance in determining environmental burdens can help to restrict the selection of OWF locations to a near-optimal set. The comparison of scenarios which are different only in one site-related factor demonstrated that water depth is the primary determining factor of environmental performance. A similar conclusion can be found by comparing environmental performance of OWFs with different foundation types. Monopile foundation OWFs, which are suitable for shallow water depths, are superior to gravity-based foundation, tripod, and floating OWFs in environmental performance. One precaution should be taken about the conclusion. Since the environmental impact contribution of cables to whole OWF decreases with wind farm scale, the large utility-scaled OWF with 100 wind turbines assumption compared to other site-related factors might magnify the influence of water depth (foundation type) on the total environmental loading.

Sensitivity analysis also revealed that the increase in electricity generation from moving OWFs further from shore is generally offset by greater environmental burdens associated with materials for creating foundation as well as greater transportation requirements for installation, maintenance, and decommissioning.

3-7-2. Environmental performance affected by macro-siting of OWFs

Macro-siting is the process of determining the location of OWFs on a large geographical scale (compared to micro-siting which determines wind turbine and cable locations) [83]. This process defines the suitable wind farm locations usually based on the criteria such as wind speed, proximity of power grid infrastructure, or accessibility to supportive transportation infrastructure such as harbors and roads. In this study, the selection of four candidate OWF locations is determined using wind speed and exclusive zone (i.e. ship routes, wildlife conservation). But the result of environmental performance shows that further discussion is needed for some less discussed macro-siting factors, including local manufacture for transport saving and power generation mix.

The benefits from locally manufacturing wind farm components include not only greater job opportunities and economic development, but also better environmental performance of OWFs as well. The reason for improved environmental performance is highly related to the reduction in transport. The reduced fuel consumption as well as the reduced need for vehicles and roads for transport is more important for the gravity based foundation OWFs where transport can contribute more than 38% of CED. The influence of distance and transport on environmental performance of wind farms was also studied by Tremeac and Meunier[58]. They found that transport contributes 34% of CO_2 emission for a 4.5MW wind turbine and suggested that wind turbine factories should be located in the places near where wind farms are to be built.

Moreover, according to the survey of wind turbine manufacturing facilities in the United States[84], the assembly plants for nacelle, blade, and tower are not all found in Michigan. The closest source for the tower and blades is from Pennsylvania and Iowa, respectively, which is the basis of the 1000km assumption of component transport in the study. This fact also implies that local manufacture of wind turbine components has potential to reduce transport and to improve environmental performance of OWFs.

Besides the transport of main wind turbine components, the transport during component fabrication stage is not insignificant. Although the LCA system boundary in this study does not account for logistics transport at fabrication stage, it is reasonable to assume that the environmental burden from transport will increase with more distributed supply chains.

Macro-siting of OWFs should take the turbine manufacturing location into account for the sake of understanding environmental performance. The LCA of wind turbine manufacturing in the Europe is based on an electricity production mix where fossil based energy accounts for a smaller portion of the electricity generated than in the United States. For example, in Germany 62% of electricity generation is fossil based electricity compared to 70% in the United States in year 2000 (Ecoinvent and USLCI data). The influence of electricity production mix on wind turbine LCA was examined by Guezuraga[57]. The electricity produced by the black coal in China, Denmark, and Germany represents 20%, 7.5% and 5.7% of total generation respectively. This is double the total CO_2 eq emissions of turbines manufactured in China compared to Germany. In the case of Michigan where a Renewable Portfolio Standard has been set for 15% of the state’s energy coming from renewable energy by 2015, as more wind energy feeds into the grid that provides the electricity for local manufacturing of wind turbines, the cleaner electricity production mix for manufacturing would make it more environmentally beneficial for OWFs to be installed there..

Macro-siting and micro-siting OWFs strategies promoted by a universal wind energy development policy tend to be ineffective in environmental performance according to this study of twenty siting scenarios. On the other words, a public policy that assigns the wind energy resource zones might be risky if only macro-siting factors are considered. The reason can be explained by the variation of environmental performance resulting from two policy approaches represented by the modeled scenarios: selecting among four locations (macro-siting strategy) or refining distance of wind turbine sites from shore (micro-siting strategy). For example, promoting OWFs located in a fixed 5 km from shore results in the GWP potentially ranging from 25.6 to 40.9 g CO_2 eq per kWh (macro-siting). This is a slightly larger variation compared to refining wind turbine sites in Oceana between 5 to 30 km scenarios where GWP ranges from 25.6 to 35.5 g CO_2 eq per kWh (micro-siting). Therefore from the perspective of environmental performance, it might be appropriate to keep a flexible of wind energy policy, such as assigning wind resource development zones.

3-7-3. Improve environmental performance through system design

Environmental performance of OWFs can be improved not only by siting strategies but also by technical design. The result of this study demonstrated the importance of foundation selection and material recycling.

In the transition zone where water depth is suitable for selection of multiple foundation types, the environmental performance of monopile foundation is advantageous compared to gravity based foundations, and a floating foundation is slightly better than a tripod foundation. In the water depth under 30m where both monopile and gravity-based foundation are economically feasible, the selection of the later technology results in a 60% greater GWP than the former (i.e. Berrien 5km and Oceana 5km). The environmental benefit from selecting a floating foundation compared to a tripod foundation is also significant (i.e. Berrien 15km and Oceana 15km).

Another method of technical design to get the environmental benefit is through the recycling of OWF materials. As was explored, the environmental outcomes of all siting scenarios are improved if recycling is applied at the end of life. One of the reasons is that wind turbine components are mostly composed of steel, which when recycled reduces environmental burdens compared to virgin steel. Because they have a higher proportion of steel, monopile and tripod foundations have a higher percentage of improvement from recycling.

The benefit of material recycling is also dependent on transport distances and electricity production mix since less transport and cleaner electricity production decreases the environmental impact during the recycling process.

3-7-4. Compare OWF LCA to past studies

Comparing the GWP of the 20 siting scenarios to previous LCA research shows that their results fall within the range of results present in other work. As highlighted in the Figure 3-10, the highest and lowest GWP of studied OWFs varies from 25.6 to 47.3 g CO_2 eq / kWh. These values are higher compared to the average of previous studies. The lower range GWP values of those studies may be attributed to several aspects. First, some models consider land–based wind turbines, which generally have simpler foundations with lower material and energy demands. Another reason is that some studies use higher capacity factor (as high as 54%) and lack of considering energy loss caused by wake effect and transmission. More energy generation is thus beneficial for GWP performance measured in terms of CO_2 eq / kWh. Finally, conceptual models can cause the highly varied result due to the use of incomplete data and uncertain input assumptions such as energy and material consumption at operation and maintenance stage.

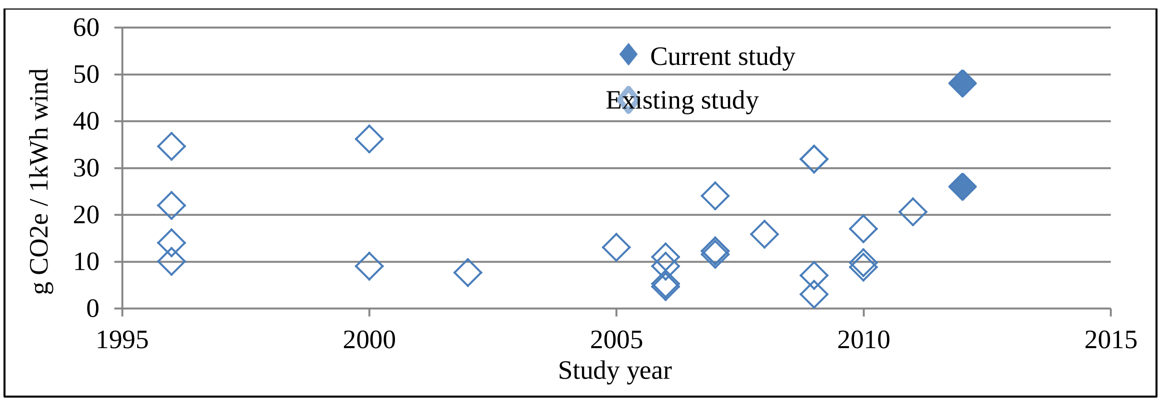


Figure 3-10 GWP of previous LCA studies in literature along with this study

The differences between the highest GWP value scenario and previous studies should also be considered. This study includes more accurate data for representing the installation stage as well as operation and maintenance stage. The broad system boundary results in larger environmental burdens because the transport distance of the wind turbine components is also assumed 1000 km. This supply chain issue is not well documented in the previous studies. However, it is very crucial for siting scenario especially with gravity based foundations which require transport of heavy cement and gravel for long distance. The question about the transport distance of the supply chain is not completely addressed in our study due to the lack of logistics transport data at fabrication stage. This would be a beneficial topic for future research.

3-8 Conclusions

A process-based LCA of OWFs was conducted to understand the best wind farm location measured by environmental performance per unit of wind energy generated. Twenty scenarios for OWFs in the Great Lakes of Michigan were examined with each having one hundred 3MW wind turbines located 5 to 30 km offshore of four different counties. Each siting scenario is dependent on the locational conditions, which determines the foundation type and the length of collection and transmission cables. The system boundary of the analyzed siting scenarios includes the stages of component manufacturing, wind farm installation, operation and maintenance, and end of life.

The results show that siting OWFs closer to the coastline generally leads to better environmental performance because the benefit of moving OWFs farther offshore for more energy generation is outweighed by the increase of environmental burden associated with manufacturing, operating, maintaining and decommissioning the OWFs. The best environmental performance scenario (Oceana 5km) has average energy generation but excellent environmental performance among the twenty studied scenarios. The reason for this is the shallow water depth in near-shore waters allow for monopile foundations to be used economically. Hence, distance from shore becomes one of the most important factors in determining the GWP, AP and CED results. Comparing the environmental performance difference of OWFs located within a small versus a large geographical scale also suggests that a universal policy to promote wind industry development in an assigned zone is sub-optimal. Policy flexibility allowing micro-siting or macro-siting strategies to respond to spatial differences may be more effective in achieving the goal of reducing the environmental impact from a life-cycle perspective.

This study also found that environmental performance of OWFs can be improved not only through siting strategies, but also by system design. As shown in the results, improvement of steel manufacturing and recycling is crucial for OWF scenarios with monopile and tripod foundation because steel requires the most significant portion of energy consumption and CO2 emission and acidification gases emission. For OWF scenarios with gravity-based foundations, reducing transport distance become more important because the requirement of transporting heavy cement and gravel over longer distances causes bad performance in all environmental indexes. Finally, the study also shows that recycling OWF components in the end of life is one of the strategies that can improve environmental performance almost in every index addressed.

The performance of GWP for the twenty OWF scenarios compared to previous studies is worse than the average, but falls within the range of previous work. The lower results from previous LCA studies of OWF may be attributed to being based on land-based wind turbines that do not need a complicated foundation, or from assuming a higher capacity. Moreover, the fast growth of OWF development in recent years that provides more data in installation and operation and maintenance stages, which can help to realistically assess environmental impact.

Future LCA studies of OWFs should consider the following aspects in more depth. First, given that transport distance is an important factor driving the environmental performance, the transport of supply chain data should be included if logistics transport data is accessible. Doing so will help understand the effect of localized manufacturing on reducing energy consumption and pollution emissions during transport. The influence of transporting cement and gravel for gravity-based foundation OWF has been examined in this study. Another aspect worth further exploration is analyses of wind turbine arrays for large scale OWFs. Their arrangement can influence the generation of wind energy as well as the material consumption for foundation and cables. Understanding the trade-off of benefit and cost in terms of environmental performance would be helpful in wind farm siting decisions. Finally, the evaluation of life cycle environmental impacts for OWFs can be extended to assess social impacts. This social LCA complements the insufficient information of environmental LCA in the decision making from the perspective of sustainability. A more comprehensive picture of the OWF's life cycle impacts can thus include the assessments, such as visual impact of OWFs on communities, displaced pollutant emissions from fossil fuels, and new job creation.

Appendix C: Life-cycle Inventory of Offshore Wind Farms

Table C-1 Life cycle inventory of wind turbine moving parts

Foreground processes with respective inputs	Amount	Unit	Reference
One unit of VESTAS V112 3 MW wind turbine	**607.50**	**t**	
One unit of VESTAS V112 3 MW wind turbine without concrete and gravel	**423.16**	**t**	
Concrete and gravel for one Unit of VESTAS V112 3 MW WT	**184.34**	**t**	
One unit of VESTAS V112 3 MW wind turbine without tower and WT misc	**141.80**	**t**	
Wind turbine misc	**68.75**	**t**	
Lubricating oil, at plant/RER U	1.73	t	Vestas V112 3MW
Propylene glycol, liquid, at plant/RER U	2.42	t	Vestas V112 3MW
Epoxy resin, liquid, at plant/RER U	8.21	t	Vestas V112 3MW
Polyvinylchloride, bulk polymerised, at plant/RER U	5.26	t	Vestas V112 3MW
Polyethylene, HDPE, granulate, at plant/RER U	0.04	t	Vestas V112 3MW
Polyvinylchloride, bulk polymerised, at plant/RER U	0.15	t	Vestas V112 3MW
Synthetic rubber, at plant/RER U	63.30	t	Vestas V112 3MW
Diesel, burned in building machine/ GLO/ MJ	171385.20	MJ	Vestas V112 3MW
Electricity, at grid, Eastern US/US	136069.20	kWh	Vestas V112 3MW
Natural gas, burned in industrial furnace >100kW/RER U	55726.80	MJ	Vestas V112 3MW
Heat from waste, at municipal waste incineration plant/CH U	96712.80	MJ	Vestas V112 3MW
Heat, at cogen 1MWe lean burn, allocation exergy/RER U	96712.80	MJ	Vestas V112 3MW
Rotor blades	**24.68**	**t**	
Steel, low-alloyed, at plant/RER U	1.23	t	Vestas V112 3MW
Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U	23.44	t	Vestas V112 3MW
Hub	**24.50**	**t**	
Aluminium, production mix, at plant/RER U	1.23	t	Vestas V112 3MW
Cast iron, at plant/RER U	23.28	t	Vestas V112 3MW
Sheet rolling, aluminium/RER U	1.23	t	Vestas V112 3MW
Generator	**11.70**	**t**	
Steel, low-alloyed, at plant/RER U	6.84	t	Vestas V112 3MW
Chromium steel 18/8, at plant/RER U	0.36	t	Vestas V112 3MW
Copper, at regional storage/RER U	4.20	t	Vestas V112 3MW
Silica sand, at plant/DE U	0.30	t	Vestas V112 3MW
Sheet rolling, chromium steel/RER U	0.36	t	Vestas V112 3MW
Gearbox	**39.00**	**t**	
Chromium steel 18/8, at plant/RER U	38.22	t	Vestas V112 3MW
Copper, at regional storage/RER U	0.39	t	Vestas V112 3MW
Aluminium, production mix, at plant/RER U	0.39	t	Vestas V112 3MW
Sheet rolling, aluminium/RER U	0.39	t	Vestas V112 3MW
Sheet rolling, chromium steel/RER U	38.22	t	Vestas V112 3MW
Nacelle other	**34.50**	**t**	

Cast iron, at plant/RER U	15.75	t	Vestas V112 3MW
Steel, low-alloyed, at plant/RER U	14.75	t	Vestas V112 3MW
Copper, at regional storage/RER U	0.25	t	Vestas V112 3MW
Aluminium, production mix, at plant/RER U	3.75	t	Vestas V112 3MW
Sheet rolling, aluminium/RER U	3.75	t	Vestas V112 3MW
Wire drawing, copper/RER U	0.25	t	Vestas V112 3MW
LV transformer(transforms the voltage from the generating voltage around 700 V, up to a medium- voltage level between 30-36 kV (Negra et al. 2006)	**7.43**	**t**	
Steel, low-alloyed, at plant/RER U	4.95	t	Vestas V112 3MW
Copper, at regional storage/RER U	2.25	t	Vestas V112 3MW
Silica sand, at plant/DE U	0.23	t	Vestas V112 3MW
Wire drawing, copper/RER U	2.13	t	Vestas V112 3MW
Tower (100 meter hub height)	**199.34**	**t**	
Steel, low-alloyed, at plant/RER U	195.00	t	Vestas V112 3MW
Concrete, normal, at plant	1.81	m3	Vestas V112 3MW
Sheet rolling, steel/RER U	195.00	t	Vestas V112 3MW
Welding, arc, steel/RER U	342.00	m	Vestas V112 3MW
Gravel, unspecified, at mine/CH U	180.00	t	Vestas V112 3MW
Transport and installation			
Transport, single unit truck, gasoline powered/US, 1000 km	515330.89	tkm	
Lorry 40t/RER/I U	0.03	unit	
Maintenance, lorry 40t/CH/I U	0.03	unit	
Road/CH/I U	1.31	ma	
Operation, maintenance, road/CH/I U	0.11	ma	
Tugboats for jack-up vessel (installation WT)	15484.80	l	
Jack- up for transport and installation of turbines (installation WT)	4080.00	l	
Disposal, lorry 40t/CH/I U	0.03	unit	
Disposal, road/RER/I U	1.31	ma	
Decommission and transport			
Transport, single unit truck, gasoline powered/US, 1000 km	515330.89	tkm	
Lorry 40t/RER/I U	0.03	unit	
Maintenance, lorry 40t/CH/I U	0.03	unit	
Road/CH/I U	1.31	ma	
Operation, maintenance, road/CH/I U	0.11	ma	
Jack- up for transport and removal of turbines (WT EOL)	4080.00	l	
Tugboats for jack-up vessel (WT EOL)	15484.80	l	
Disposal, lorry 40t/CH/I U	0.03	unit	
Disposal, road/RER/I U	1.31	ma	
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	0.04	t	SimaPro
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH U	5.41	t	SimaPro

Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U	12.35	t	SimaPro
Landfill of ferro metals EU-27	312.83	t	
incineration	86.74	t	
HV transformer			
Electricity, production mix US/US U	39027.60	kWh	Birkeland, 2011
Lubricating oil, at plant/RER U	16.05	t	Birkeland, 2011
Steel, low-alloyed, at plant/RER U	37.69	t	Birkeland, 2011
Copper, at regional storage/RER U	8.10	t	Birkeland, 2011
Aluminium, production mix, at plant/RER U	0.66	t	Birkeland, 2011
Natural gas, burned in industrial furnace >100kW/RER U	598023.00	MJ	Birkeland, 2011
Kraft paper, unbleached, at plant/RER U	0.50	t	Birkeland, 2011
Sulphate pulp, average, at regional storage/RER U	1.77	t	Birkeland, 2011
Glass fibre, at plant/RER U	0.37	t	Birkeland, 2011
Alkyd paint, white, 60% in solvent, at plant/RER U	0.03	t	Birkeland, 2011
Epoxy resin insulator (Al2O3), at plant/RER U	0.06	t	Birkeland, 2011
Installation and Transport, (from prod. site to harbour, 1000 km)			
Transport, single unit truck, gasoline powered/US	65224.80	tkm	
Crane vessel for installation of topside (installation HV – transf.)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Tugboats for barge for transport of substation (installation HV – transf.)	15484.80	l	(Clean Air Agency 1999)
Lorry 40t/RER/I U	3.70E-03	unit	
Maintenance, lorry 40t/CH/I U	3.70E-03	unit	
Road/CH/I U	2.12E-07	ma	
Operation, maintenance, road/CH/I U	1.76E-08	ma	
Disposal, lorry 40t/CH/I U	3.70E-03	unit	
Disposal, road/RER/I U	2.12E-07	unit	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	65224.80	tkm	
Crane vessel for installation of topside (installation HV – transf.)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Tugboats for barge for transport of substation (installation HV – transf.)	15484.80	l	(Clean Air Agency 1999)
Lorry 40t/RER/I U	3.70E-03	unit	
Maintenance, lorry 40t/CH/I U	3.70E-03	unit	
Road/CH/I U	2.12E-07	ma	
Operation, maintenance, road/CH/I U	1.76E-08	ma	
Disposal, lorry 40t/CH/I U	3.70E-03	unit	
Disposal, road/RER/I U	2.12E-07	unit	
Landfill of ferro metals EU-27	46.45	t	
Disposal, inert waste, 5% water, to inert material landfill/CH U	18.78	t	

Table C-2 Life cycle inventory of gravity based foundation

Foreground processes with respective inputs	Amount	Unit	Reference
Foundation (gravity based) at water depth of 15 meter is treated as baseline case			**Huron 5 km**
distance from shore	**5.00**	**km**	
Weight per foundation	**18464.25**	**t**	
Material and manufacture			
Reinforcing steel, at plant/RER U	336.00	t	Anholt Offshore Wind Farm
Concrete, normal, at plant	1027.00	m3	Anholt Offshore Wind Farm, one cubic meter of concrete equals 2.4 t
Gravel, unspecified, at mine/CH U (Ballast)	12200.00	t	Anholt Offshore Wind Farm, 7176 m3 * 1.7 t/m3
Installation of Gravity based foundation and Transport, (from prod. site to harbour, 500 km)			
Gravel, unspecified, at mine/CH U(stone bed, 2m depth per base)	1668.97	t	Anholt Offshore Wind Farm
Gravel, unspecified, at mine/CH U(scour protection)	1794.48	t	Anholt Offshore Wind Farm
Occupation, water bodies, artificial	35837.72	m2a	
Transformation, from sea and ocean	1194.59	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	1194.59	m2	
Barge for excavator	7200.00	l	(Vroon offshore services 2010), 3 days transport per turbine
Excavator	32.76	l	(Ecoinvent 2010)
Barge for disposal of seabed material	846.65	l	(Vroon offshore services 2010)
Vessel for transport of rock for stone bed	846.65	l	(Vroon offshore services 2010)
Vessel for dumping of rock for stone bed	7200.00	l	(Vroon offshore services 2010)
Transport, single unit truck, gasoline powered/US	9232124.38	tkm	
Tugboats for transport of foundations (Installation foundation)	43700.80	l	(Clean Air Agency 1999)
Tugboats for transport of jack-up vessel (installation foundation)	580.63	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Vessel for transport of rock for scour protection	846.65	l	(Vroon offshore services 2010)
Vessel for dumping of rock for scour protection	7200.00	l	(Vroon offshore services 2010)
Lorry 40t/RER/I U	0.43	unit	
Maintenance, lorry 40t/CH/I U	0.43	unit	
Road/CH/I U	4.12	ma	
Operation, maintenance, road/CH/I U	0.34	ma	
Disposal, lorry 40t/CH/I U	0.43	unit	
Disposal, road/RER/I U	4.12	ma	
Transport and decommission, (from harbour to treatment, 500 km)			
Tugboats for transport of jack-up vessel (installation foundation)	580.63	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Tugboats for transport of foundations (Installation foundation)	43700.80	l	(Clean Air Agency

			1999)
Transport, single unit truck, gasoline powered/US	7500400.00	tkm	
Lorry 40t/RER/I U	0.35	unit	
Maintenance, lorry 40t/CH/I U	0.35	unit	
Road/CH/I U	3.35	ma	
Operation, maintenance, road/CH/I U	0.28	ma	
Disposal, lorry 40t/CH/I U	0.35	unit	
Disposal, road/RER/I U	3.35	ma	
Landfill of ferro metals EU-27	336.00	t	
Disposal, inert waste, 5% water, to inert material landfill/CH U	18128.25	t	
Foundation (gravity based) at water depth of 20 meter			**Berrien 5 km**
distance from shore	**5.00**	**km**	
Weight per turbine	**18474.00**	**t**	
Material and manufacture			
Reinforcing steel, at plant/RER U	336.00	t	Anholt Offshore Wind Farm
Concrete, normal, at plant	1027.00	m3	Anholt Offshore Wind Farm, one cubic meter of concrete equals 2.4 t
Gravel, unspecified, at mine/CH U (Ballast)	12200.00	t	Anholt Offshore Wind Farm, 7176 m3 * 1.7 t/m3
adjusted Tower for water depth(5 meter deeper)	**9.75**	**t**	
Steel, low-alloyed, at plant/RER U	9.75	t	Vestas V90 3MW, 1/20 of the 100 meter height of tower equals 5 meter
Sheet rolling, steel/RER U	9.75	t	Vestas V90 3MW
Installation of Gravity based foundation and Transport, (from prod. site to harbour, 500 km)			
Gravel, unspecified, at mine/CH U(stone bed, 2m depth per base)	1668.97	t	Anholt Offshore Wind Farm
Gravel, unspecified, at mine/CH U(scour protection)	1794.48	t	Anholt Offshore Wind Farm
Occupation, water bodies, artificial	35837.72	m2a	
Transformation, from sea and ocean	1194.59	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	1194.59	m2	
Barge for excavator	7200.00	l	(Vroon offshore services 2010), 3 days transport per turbine
Excavator	32.76	l	(Ecoinvent 2010)
Barge for disposal of seabed material	846.65	l	(Vroon offshore services 2010)
Vessel for transport of rock for stone bed	846.65	l	(Vroon offshore services 2010)
Vessel for dumping of rock for stone bed	7200.00	l	(Vroon offshore services 2010)
Transport, single unit truck, gasoline powered/US	9236999.38	tkm	
Tugboats for transport of foundations (Installation foundation)	43700.80	l	(Clean Air Agency 1999)
Tugboats for transport of jack-up vessel (installation foundation)	580.63	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)

Vessel for transport of rock for scour protection	846.65	l	(Vroon offshore services 2010)
Vessel for dumping of rock for scour protection	7200.00	l	(Vroon offshore services 2010)
Lorry 40t/RER/I U	0.43	unit	
Maintenance, lorry 40t/CH/I U	0.43	unit	
Road/CH/I U	4.12	ma	
Operation, maintenance, road/CH/I U	0.34	ma	
Disposal, lorry 40t/CH/I U	0.43	unit	
Disposal, road/RER/I U	4.12	ma	
Transport and decommission, (from harbour to treatment, 500 km)			
Tugboats for transport of jack-up vessel (installation foundation)	580.63	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Tugboats for transport of foundations (Installation foundation)	43700.80	l	(Clean Air Agency 1999)
Transport, single unit truck, gasoline powered/US	7505275.00	tkm	
Lorry 40t/RER/I U	0.35	unit	
Maintenance, lorry 40t/CH/I U	0.35	unit	
Road/CH/I U	3.35	ma	
Operation, maintenance, road/CH/I U	0.28	ma	
Disposal, lorry 40t/CH/I U	0.35	unit	
Disposal, road/RER/I U	3.35	ma	
Landfill of ferro metals EU-27	345.75	t	
Disposal, inert waste, 5% water, to inert material landfill/CH U	18128.25	t	

Table C-3 Life cycle inventory of monofile foundation

Foreground processes with respective inputs	Amount	Unit	Reference
Foundation (monopile) at water depth of 20 meter is treated as base case			**Huron 10 km**
OWF distance offshore	10.00	km	
Weight per turbine	1599.81	ton	
material and manufacture			
Steel, low-alloyed, at plant/RER U (monopile)	276.00	t	Anholt Offshore Wind Farm
Steel, low-alloyed, at plant/RER U(transition piece)	169.50	t	Anholt Offshore Wind Farm
Sheet rolling, steel/RER U	445.50	t	
Concrete, normal, at plant/CH U	21.30	t	Anholt Offshore Wind Farm
Installation of monopile foundation and transport from production site to harbor (1000km for steel and 500 km for stone)			
Gravel, unspecified, at mine/CH U(per base)	687.51	t	Anholt Offshore Wind Farm
Occupation, water bodies, artificial	8740.25	m2a	
Transformation, from sea and ocean	291.34	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	291.34	m2	
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)

Pump/generator for injection of grout	4440.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	799904.63	tkm	
Tugboats for transport of foundations (Installation foundation)	3311.93	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	1161.27	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Vessel for transport of rock for scour protection	513.32	l	(Vroon offshore services 2010)
Vessel for dumping of rock for scour protection	2911.80	l	(Vroon offshore services 2010)
Lorry 40t/RER/I U	0.04	unit	
Maintenance, lorry 40t/CH/I U	0.04	unit	
Road/CH/I U	1.44	ma	
Operation, maintenance, road/CH/I U	0.12	ma	
Disposal, lorry 40t/CH/I U	0.04	unit	
Disposal, road/RER/I U	1.44	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	456150.00	tkm	
Barge for pump/generator (Remove foundation)	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout (Remove foundation)	4440.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (Remove foundation)	3311.93	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	1161.27	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.02	unit	
Maintenance, lorry 40t/CH/I U	0.02	unit	
Road/CH/I U	1.29	ma	
Operation, maintenance, road/CH/I U	0.11	ma	
Disposal, lorry 40t/CH/I U	0.02	unit	
Disposal, road/RER/I U	1.29	ma	
Landfill of ferro metals EU-27	445.50	t	
Landfill of gravel	708.81	t	
Foundation (monopile) at water depth of 25 meter			**Ottawa 5km and Oceana 5km**
OWF distance offshore	5.00	km	
Weight per turbine	1619.31	ton	
material and manufacture			
Steel, low-alloyed, at plant/RER U (monopile)	276.00	t	Anholt Offshore Wind Farm
Steel, low-alloyed, at plant/RER U(transition piece)	169.50	t	Anholt Offshore Wind Farm
Sheet rolling, steel/RER U	455.25	t	

Concrete, normal, at plant/CH U	21.30	t	Anholt Offshore Wind Farm
adjusted foundation for water depth(5 meter deeper)	**9.75**	**t**	
Steel, low-alloyed, at plant/RER U	9.75	t	Vestas V90 3MW, 1/20 of the 100 meter height of tower equals 5 meter
Installation of monopile foundation and transport from production site to harbor (1000km for steel and 500 km for stone)			
Occupation, water bodies, artificial	8740.25	m2a	
Transformation, from sea and ocean	291.34	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	291.34	m2	
Gravel, unspecified, at mine/CH U(per base)	687.51	t	Anholt Offshore Wind Farm
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout	4440.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	809654.63	tkm	
Tugboats for transport of foundations (Installation foundation)	2731.30	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	580.63	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Vessel for transport of rock for scour protection	423.33	l	(Vroon offshore services 2010)
Vessel for dumping of rock for scour protection	2911.80	l	(Vroon offshore services 2010)
Lorry 40t/RER/I U	0.04	unit	
Maintenance, lorry 40t/CH/I U	0.04	unit	
Road/CH/I U	1.44	ma	
Operation, maintenance, road/CH/I U	0.12	ma	
Disposal, lorry 40t/CH/I U	0.04	unit	
Disposal, road/RER/I U	1.44	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	465900.00	tkm	
Barge for pump/generator (Remove foundation)	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout (Remove foundation)	4440.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (Remove foundation)	2731.30	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	580.63	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.02	unit	
Maintenance, lorry 40t/CH/I U	0.02	unit	
Road/CH/I U	1.29	ma	
Operation, maintenance, road/CH/I U	0.11	ma	
Disposal, lorry 40t/CH/I U	0.02	unit	

Disposal, road/RER/I U	1.29	ma	
Landfill of ferro metals EU-27	455.25	t	
Landfill of gravel	708.81	t	
Foundation (monopile) at water depth of 30 meter			**Berrien 10 km**
OWF distance offshore	10.00	km	
Weight per turbine	1638.81	ton	
material and manufacture			
Steel, low-alloyed, at plant/RER U (monopile)	276.00	t	Anholt Offshore Wind Farm
Steel, low-alloyed, at plant/RER U(transition piece)	169.50	t	Anholt Offshore Wind Farm
Sheet rolling, steel/RER U	465.00	t	
Concrete, normal, at plant/CH U	21.30	t	Anholt Offshore Wind Farm
adjusted foundation for water depth(10 meter deeper)	**19.50**	**t**	
Steel, low-alloyed, at plant/RER U	19.50	t	Vestas V90 3MW, 1/10 of the 100 meter height of tower equals 5 meter
Installation of monopile foundation and transport from production site to harbor (1000km for steel and 500 km for stone)			
Occupation, water bodies, artificial	8740.25	m2a	
Transformation, from sea and ocean	291.34	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	291.34	m2	
Gravel, unspecified, at mine/CH U(per base)	687.51	t	Anholt Offshore Wind Farm
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout	4440.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	819404.63	tkm	
Tugboats for transport of foundations (Installation foundation)	3311.93	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	1161.27	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Vessel for transport of rock for scour protection	513.32	l	(Vroon offshore services 2010)
Vessel for dumping of rock for scour protection	2911.80	l	(Vroon offshore services 2010)
Lorry 40t/RER/I U	0.04	unit	
Maintenance, lorry 40t/CH/I U	0.04	unit	
Road/CH/I U	1.44	ma	
Operation, maintenance, road/CH/I U	0.12	ma	
Disposal, lorry 40t/CH/I U	0.04	unit	
Disposal, road/RER/I U	1.44	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	475650.00	tkm	
Barge for pump/generator (Remove foundation)	2400.00	l	(Vroon offshore services 2010)

Pump/generator for injection of grout (Remove foundation)	4440.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (Remove foundation)	3311.93	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	1161.27	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.02	unit	
Maintenance, lorry 40t/CH/I U	0.02	unit	
Road/CH/I U	1.29	ma	
Operation, maintenance, road/CH/I U	0.11	ma	
Disposal, lorry 40t/CH/I U	0.02	unit	
Disposal, road/RER/I U	1.29	ma	
Landfill of ferro metals EU-27	465.00	t	
Landfill of gravel	708.81	t	

Table C-4 Life cycle inventory of tripod foundation

Foreground processes with respective inputs	Amount	Unit	Reference
Foundation (tripod) at water depth of 35 meter is defined as the base case			**Huron 15 km**
OWF distance from shore	15.00	km	
Weight per foundation	3371.90	t	
Material and manufacture			
Steel, low-alloyed, at plant/RER U(Y-frame)	807.00	t	Offshore Wind Power Systems of Texas LLC
Steel, low-alloyed, at plant/RER U (3 piles)	847.00	t	Offshore Wind Power Systems of Texas LLC
sheet rolling, steel	1654.00	t	
Concrete, normal, at plant/CH U	63.90	t	Anholt Offshore Wind Farm
Installation of tripod foundation and Transport, (from prod. site to harbour, 1000 km)			
Occupation, water bodies, artificial	22902.21	m2a	
Transformation, from sea and ocean	763.41	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	763.41	m2	
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	1685950.00	tkm	
Tugboats for transport of foundations (Installation foundation)	7785.13	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	1741.90	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.08	unit	
Maintenance, lorry 40t/CH/I U	0.08	unit	
Road/CH/I U	4.51	ma	
Operation, maintenance, road/CH/I U	0.38	ma	

Disposal, lorry 40t/CH/I U	0.08	unit	
Disposal, road/RER/I U	4.51	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	1685950.00	tkm	
Barge for pump/generator (remove foundation)	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout (remove foundation)	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (remove foundation)	7785.13	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	1741.90	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.08	unit	
Maintenance, lorry 40t/CH/I U	0.08	unit	
Road/CH/I U	4.51	ma	
Operation, maintenance, road/CH/I U	0.38	ma	
Disposal, lorry 40t/CH/I U	0.08	unit	
Disposal, road/RER/I U	4.51	ma	
Landfill of ferro metals EU-27	1654.00	t	
Landfill of gravel	63.90	t	
Foundation (tripod) at water depth of 35 meter is defined as the base case			**Huron 20 km**
OWF distance from shore	20.00	km	
Weight per foundation	1717.90	t	
Material and manufacture			
Steel, low-alloyed, at plant/RER U(Y-frame)	807.00	t	Offshore Wind Power Systems of Texas LLC
Steel, low-alloyed, at plant/RER U (3 piles)	847.00	t	Offshore Wind Power Systems of Texas LLC
Concrete, normal, at plant/CH U	63.90	t	Anholt Offshore Wind Farm
sheet rolling, steel	1654.00	t	
Installation of tripod foundation and Transport, (from prod. site to harbour, 1000 km)			
Occupation, water bodies, artificial	22902.21	m2a	
Transformation, from sea and ocean	763.41	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	763.41	m2	
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	1685950.00	tkm	
Tugboats for transport of foundations (Installation foundation)	8946.40	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	2322.53	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.08	unit	

Maintenance, lorry 40t/CH/I U	0.08	unit	
Road/CH/I U	4.51	ma	
Operation, maintenance, road/CH/I U	0.38	ma	
Disposal, lorry 40t/CH/I U	0.08	unit	
Disposal, road/RER/I U	4.51	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	1685950.00	tkm	
Barge for pump/generator (remove foundation)	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout (remove foundation)	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (remove foundation)	8946.40	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	2322.53	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.08	unit	
Maintenance, lorry 40t/CH/I U	0.08	unit	
Road/CH/I U	4.51	ma	
Operation, maintenance, road/CH/I U	0.38	ma	
Disposal, lorry 40t/CH/I U	0.08	unit	
Disposal, road/RER/I U	4.51	ma	
Landfill of ferro metals EU-27	1654.00	t	
Landfill of gravel	63.90	t	
Foundation (tripod) at water depth of 50 meter			**Huron 30 km**
OWF distance from shore	30.00	km	
Weight per foundation	2035.53	t	
Material and manufacture			
Steel, low-alloyed, at plant/RER U(Y-frame)	807.00	t	Offshore Wind Power Systems of Texas LLC
Steel, low-alloyed, at plant/RER U (3 piles)	847.00	t	Offshore Wind Power Systems of Texas LLC
Concrete, normal, at plant/CH U	63.90	t	Anholt Offshore Wind Farm
sheet rolling, steel	1971.63	t	
adjusted foundation for water depth(15 meter deeper)	**317.63**	**t**	
Steel, low-alloyed, at plant/RER U	317.63	t	Vestas V90 3MW, piles are driven 5 meter under ground surface. 40 meter long for base case one pile
Installation of tripod foundation and Transport, (from prod. site to harbour, 1000 km)			
Occupation, water bodies, artificial	22902.21	m2a	
Transformation, from sea and ocean	763.41	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	763.41	m2	
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)

Pump/generator for injection of grout	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	2003575.00	tkm	
Tugboats for transport of foundations (Installation foundation)	16903.40	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	3483.80	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.09	unit	
Maintenance, lorry 40t/CH/I U	0.09	unit	
Road/CH/I U	5.37	ma	
Operation, maintenance, road/CH/I U	0.45	ma	
Disposal, lorry 40t/CH/I U	0.09	unit	
Disposal, road/RER/I U	5.37	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	2003575.00	tkm	
Barge for pump/generator (remove foundation)	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout (remove foundation)	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (remove foundation)	16903.40	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	3483.80	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.09	unit	
Maintenance, lorry 40t/CH/I U	0.09	unit	
Road/CH/I U	5.37	ma	
Operation, maintenance, road/CH/I U	0.45	ma	
Disposal, lorry 40t/CH/I U	0.09	unit	
Disposal, road/RER/I U	5.37	ma	
Landfill of ferro metals EU-27	1971.63	t	
Landfill of gravel	63.90	t	
Foundation (tripod) at water depth of 40 meter			**Berrien 15 km**
OWF distance from shore	15.00	km	
Weight per foundation	1823.78	t	
Material and manufacture			
Steel, low-alloyed, at plant/RER U(Y-frame)	807.00	t	Offshore Wind Power Systems of Texas LLC
Steel, low-alloyed, at plant/RER U (3 piles)	847.00	t	Offshore Wind Power Systems of Texas LLC
Concrete, normal, at plant/CH U	63.90	t	Anholt Offshore Wind Farm
sheet rolling, steel	1759.88	t	
adjusted foundation for water depth(15 meter deeper)	**105.88**	**t**	

Steel, low-alloyed, at plant/RER U	105.88	t	Vestas V90 3MW, piles are driven 5 meter under ground surface. 40 meter long for base case one pile
Installation of tripod foundation and Transport, (from prod. site to harbour, 1000 km)			
Occupation, water bodies, artificial	22902.21	m2a	
Transformation, from sea and ocean	763.41	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	763.41	m2	
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	1791825.00	tkm	
Tugboats for transport of foundations (Installation foundation)	7785.13	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	1741.90	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.08	unit	
Maintenance, lorry 40t/CH/I U	0.08	unit	
Road/CH/I U	4.73	ma	
Operation, maintenance, road/CH/I U	0.39	ma	
Disposal, lorry 40t/CH/I U	0.08	unit	
Disposal, road/RER/I U	4.73	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	1791825.00	tkm	
Barge for pump/generator (remove foundation)	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout (remove foundation)	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (remove foundation)	7785.13	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	1741.90	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.08	unit	
Maintenance, lorry 40t/CH/I U	0.08	unit	
Road/CH/I U	4.73	ma	
Operation, maintenance, road/CH/I U	0.39	ma	
Disposal, lorry 40t/CH/I U	0.08	unit	
Disposal, road/RER/I U	4.73	ma	
Landfill of ferro metals EU-27	1759.88	t	
Landfill of gravel	63.90	t	
Foundation (tripod) at water depth of 50 meter			**Berrien 20 km**
OWF distance from shore	20.00	km	
Weight per foundation	4007.15	t	
Material and manufacture			

Steel, low-alloyed, at plant/RER U(Y-frame)	807.00	t	Offshore Wind Power Systems of Texas LLC
Steel, low-alloyed, at plant/RER U (3 piles)	847.00	t	Offshore Wind Power Systems of Texas LLC
sheet rolling, steel	1971.63	t	
Concrete, normal, at plant/CH U	63.90	t	Anholt Offshore Wind Farm
adjusted foundation for water depth(15 meter deeper)	**317.63**	**t**	
Steel, low-alloyed, at plant/RER U	317.63	t	Vestas V90 3MW, piles are driven 5 meter under ground surface. 40 meter long for base case one pile
Installation of tripod foundation and Transport, (from prod. site to harbour, 1000 km)			
Occupation, water bodies, artificial	22902.21	m2a	
Transformation, from sea and ocean	763.41	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	763.41	m2	
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	2003575.00	tkm	
Tugboats for transport of foundations (Installation foundation)	13419.60	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	2322.53	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.09	unit	
Maintenance, lorry 40t/CH/I U	0.09	unit	
Road/CH/I U	5.37	ma	
Operation, maintenance, road/CH/I U	0.45	ma	
Disposal, lorry 40t/CH/I U	0.09	unit	
Disposal, road/RER/I U	5.37	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	2003575.00	tkm	
Barge for pump/generator (remove foundation)	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout (remove foundation)	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (remove foundation)	13419.60	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	2322.53	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.09	unit	
Maintenance, lorry 40t/CH/I U	0.09	unit	
Road/CH/I U	5.37	ma	
Operation, maintenance, road/CH/I U	0.45	ma	
Disposal, lorry 40t/CH/I U	0.09	unit	
Disposal, road/RER/I U	5.37	ma	

Landfill of ferro metals EU-27	1971.63	t	
Landfill of gravel	63.90	t	
Foundation (tripod) at water depth of 50 meter			**Oceana 10 km**
OWF distance from shore	10.00	km	
Weight per foundation	4007.15	t	
Material and manufacture			
Steel, low-alloyed, at plant/RER U(Y-frame)	807.00	t	Offshore Wind Power Systems of Texas LLC
Steel, low-alloyed, at plant/RER U (3 piles)	847.00	t	Offshore Wind Power Systems of Texas LLC
sheet rolling, steel	1971.63	t	
Concrete, normal, at plant/CH U	63.90	t	Anholt Offshore Wind Farm
adjusted foundation for water depth(15 meter deeper)	**317.63**	**t**	
Steel, low-alloyed, at plant/RER U	317.63	t	Vestas V90 3MW, piles are driven 5 meter under ground surface. 40 meter long for base case one pile
Installation of tripod foundation and Transport, (from prod. site to harbour, 1000 km)			
Occupation, water bodies, artificial	22902.21	m2a	
Transformation, from sea and ocean	763.41	m2	Anholt Offshore Wind Farm
Transformation, to water bodies, artificial	763.41	m2	
Barge for pump/generator	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Transport, single unit truck, gasoline powered/US	2003575.00	tkm	
Tugboats for transport of foundations (Installation foundation)	9935.80	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	1161.27	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.09	unit	
Maintenance, lorry 40t/CH/I U	0.09	unit	
Road/CH/I U	5.37	ma	
Operation, maintenance, road/CH/I U	0.45	ma	
Disposal, lorry 40t/CH/I U	0.09	unit	
Disposal, road/RER/I U	5.37	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	2003575.00	tkm	
Barge for pump/generator (remove foundation)	2400.00	l	(Vroon offshore services 2010)
Pump/generator for injection of grout (remove foundation)	13320.00	l	(Vroon offshore services 2010 and Atlas Copco QAC-1000 Generators)
Tugboats for transport of foundations (remove foundation)	9935.80	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (remove foundation)	1161.27	l	(Clean Air Agency 1999)
Jack-up for foundations (remove foundation)	4080.00	l	(Fred. Olsen Windcarrier AS 2006)

Lorry 40t/RER/I U	0.09	unit	
Maintenance, lorry 40t/CH/I U	0.09	unit	
Road/CH/I U	5.37	ma	
Operation, maintenance, road/CH/I U	0.45	ma	
Disposal, lorry 40t/CH/I U	0.09	unit	
Disposal, road/RER/I U	5.37	ma	
Landfill of ferro metals EU-27	1971.63	t	
Landfill of gravel	63.90	t	

Table C-5 Life cycle inventory of floating foundation

Foreground processes with respective inputs	Amount	Unit	Reference
Foundation (floating)			
Distance from shore	10.00	km	
Weight per turbine	5005.00	ton	
Material and manufacture			
Low alloy Steel, weight per unit (Hull)	1000.00	t	Weinzettel, 2008
Steel, sheet rolling	1000.00	t	
low alloy steel, weight per unit (anchor leg)	5.00	t	Weinzettel, 2008
Gravel, unspecified, at mine/CH U (Ballast)	2500.00	t	Weinzettel, 2008
Installation of floating foundation and Transport, (from prod. site to harbour, 1000 km for steel and 500 km for gravel)			
Concrete, normal, at plant (suction caission)	500.00	t	Weinzettel, 2008
Occupation, water bodies, artificial	651.90	m2a	
Transformation, from sea and ocean	21.73	m2	**Anholt Offshore Wind Farm**
Transformation, to water bodies, artificial	21.73	m2	
Transport, single unit truck, gasoline powered/US (foundation, ballast, suction caission)	2505000.00	tkm	
Tugboats for transport of foundations and ballast (Installation foundation)	16559.67	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	1161.27	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	8160.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	2.38	unit	
Maintenance, lorry 40t/CH/I U	2.38	unit	
Road/CH/I U	25.19	ma	
Operation, maintenance, road/CH/I U	2.10	ma	
Disposal, lorry 40t/CH/I U	2.38	unit	
Disposal, road/RER/I U	25.19	ma	
Transport and decommission, (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	2255000.00	tkm	
Tugboats for transport of foundations and ballast (Installation foundation)	13247.74	l	(Clean Air Agency 1999)
Tugboats for jack-up vessel (installation foundation)	1161.27	l	(Clean Air Agency 1999)
Jack-up for foundations (installation foundation)	8160.00	l	(Fred. Olsen Windcarrier AS 2006)
Lorry 40t/RER/I U	0.11	unit	

Maintenance, lorry 40t/CH/I U	0.11	unit	
Road/CH/I U	3.34	ma	
Operation, maintenance, road/CH/I U	0.28	ma	
Disposal, lorry 40t/CH/I U	0.11	unit	
Disposal, road/RER/I U	3.34	ma	
Landfill of ferro metals EU-27	1005.00	t	
Landfill of gravel	3000.00	t	

Table C-6 Life cycle inventory of cables

Foreground processes with respective inputs	Amount	Unit	reference
33kv Cable [functional unit], 1 km	29.00	t	
Material and processing			
Lead, at regional storage/RER U	8.00	t	
Copper, at regional storage/RER U	6.00	t	
Steel, low-alloyed, at plant/RER U	12.00	t	
Polyethylene, HDPE, granulate, at plant/RER U	2.00	t	
polypropylene, granulate, at plant/ RER/ kg	1.00	t	
Wire drawing, copper/RER U 0,106 kg	6.00	t	
Cable installation			
Gravel, unspecified, at mine/CH U (scour protection)	25.00	t	Anholt Offshore Wind Farm
Input from nature			
Occupation, water bodies, artificial	30000.00	m2a	
Transformation, from sea and ocean	1000.00	m2	
Transformation, to water bodies, artificial	1000.00	m2	
Transport, lorry >32t, EURO5 (from prod. site to harbour, 1000 km for cables and 500km for gravel)			
Pre-sweep route	2461.68	l	
Route clearance	385.68	l	Van Oord ACZ B.V., 2001
Transport, single unit truck, gasoline powered/US	29000.00	tkm	
Diesel, combusted in industrial equipment/US (in-field cable lay operation)	15163.08	l	Van Oord ACZ B.V., 2001
support vessel for in-field operation	6461.91	l	Van Oord ACZ B.V., 2001
burial support equipment for in-field operation	6300.00	l	Van Oord ACZ B.V., 2001
Transport, single unit truck, gasoline powered/US (Rock)	12500.00	tkm	
Vessel for transport of rock for scour protection	10.58	l	(Vroon offshore services 2010)
Vessel for dumping of rock for scour protection	105.88	l	(Vroon offshore services 2010)
Lorry 40t/RER/I U	0.00	unit	
Maintenance, lorry 40t/CH/I U	0.00	unit	
Road/CH/I U	0.00	ma	
Operation, maintenance, road/CH/I U	0.00	ma	
Disposal, lorry 40t/CH/I U	0.00	P	
Disposal, road/RER/I U	0.00	ma	
Inspection of cables during operation (30 years) (O&M) unit			

Inspection of cables during operation (20 years) (O&M)	168.00	l	(Vroon offshore services 2010)
cable decommission			
Transport, lorry >32t, EURO5 (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	29000.00	tkm	
Route clearance	385.68	l	Van Oord ACZ B.V., 2001
Diesel, combusted in industrial equipment/US (in-field operation)	15163.08	l	Van Oord ACZ B.V., 2001
support vessel for in-field operation	6461.91	l	Van Oord ACZ B.V., 2001
burial support equipment for in-field operation	6300.00	l	Van Oord ACZ B.V., 2001
Lorry 40t/RER/I U	0.00	unit	
Maintenance, lorry 40t/CH/I U	0.00	unit	
Road/CH/I U	0.00	ma	
Operation, maintenance, road/CH/I U	0.00	ma	
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	2.00	ton	
Disposal, polypropylene, 15.9% water, to municipal incineration/CH U	1.00	ton	
Disposal, lorry 40t/CH/I U	0.00	P	
Disposal, road/RER/I U	0.00	ma	
Landfill of ferro metals EU-27	26.00	ton	
132kv Cable (LCA system), 1 km	89.00	t	
Material and processing			
Lead, at regional storage/RER U	22.00	t	
Copper, at regional storage/RER U	28.00	t	
Steel, low-alloyed, at plant/RER U	28.00	t	
Polyethylene, HDPE, granulate, at plant/RER U	7.00	t	
polypropylene, granulate, at plant/ RER/ kg	4.00	t	
Wire drawing, copper/RER U 0,106 kg	28.00	t	
Cable installation			
Gravel, unspecified, at mine/CH U (Ballast)	25.00	t	Anholt Offshore Wind Farm
Input from nature			
Occupation, water bodies, artificial	30000.00	m2a	
Transformation, from sea and ocean	1000.00	m2	
Transformation, to water bodies, artificial	1000.00	m2	
Transport, lorry >32t, EURO5 (from prod. site to harbour, 1000 km)			
Pre-sweep route	2560.00	l	
Route clearance	484.00	l	Van Oord ACZ B.V., 2001
Transport, single unit truck, gasoline powered/US	89000.00	tkm	
Diesel, combusted in industrial equipment/US (in-field operation)	17416.16	l	Van Oord ACZ B.V., 2001
support vessel for in-field operation	6720.00	l	Van Oord ACZ B.V., 2001
burial support equipment for shore landing	6300.00	l	Van Oord ACZ B.V., 2001
Transport, single unit truck, gasoline powered/US (rock)	12500.00	tkm	
Vessel for transport of rock for scour protection	10.58	l	(Vroon offshore services 2010)

Vessel for dumping of rock for scour protection	200.00	l	(Vroon offshore services 2010)
Lorry 40t/RER/I U	0.00	unit	
Maintenance, lorry 40t/CH/I U	0.00	unit	
Road/CH/I U	0.00	ma	
Operation, maintenance, road/CH/I U	0.00	ma	
Disposal, lorry 40t/CH/I U	0.00	P	
Disposal, road/RER/I U	0.00	ma	
Inspection of cables during operation (30 years) (O&M) unit			
Inspection of cables during operation (20 years) (O&M)	672.00	l	(Vroon offshore services 2010)
cable decommission			
Transport, lorry >32t, EURO5 (from harbour to treatment, 1000 km)			
Route clearance	484.00	l	Van Oord ACZ B.V., 2001
Diesel, combusted in industrial equipment/US (shore connection)	17416.16	l	Van Oord ACZ B.V., 2001
support vessel for shore connection	6720.00	l	Van Oord ACZ B.V., 2001
shore landing for shore connection	6300.00	l	Van Oord ACZ B.V., 2001
Transport, single unit truck, gasoline powered/US	89000.00	tkm	
Lorry 40t/RER/I U	0.00	unit	
Maintenance, lorry 40t/CH/I U	0.00	unit	
Road/CH/I U	0.00	ma	
Operation, maintenance, road/CH/I U	0.00	ma	
Decommission			
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	7.00	ton	
Disposal, polypropylene, 15.9% water, to municipal incineration/CH U	4.00	ton	
Disposal, lorry 40t/CH/I U	0.00	P	
Disposal, road/RER/I U	0.00	ma	
Landfill of ferro metals EU-27	78.00	ton	
Transmission network, high voltage, 1 km on land	11.70	t	
Material and processing			
Steel, low-alloyed, at plant/RER U	0.21	t	SimaPro
Copper, at regional storage/RER U	0.27	t	SimaPro
Aluminium, production mix, at plant/RER U	3.15	t	SimaPro
Lead, at regional storage/RER U	0.13	t	SimaPro
Packaging film, LDPE, at plant/RER U	0.07	t	SimaPro
Polyvinylchloride, at regional storage/RER U	0.07	t	SimaPro
Steel, converter, unalloyed, at plant/RER U	7.74	t	SimaPro
Light fuel oil, at regional storage/RER U	0.07	t	SimaPro
Cable installation			
Input from nature			
Occupation, industrial area, built up	572.00	m2a	
Occupation, industrial area, vegetation	685.00	m2a	

Transformation, from arable	23.30	m2	
Transformation, from forest	18.60	m2	
Transformation, to industrial area, built up	19.10	m2	
Transformation, to industrial area, vegetation	22.80	m2	
Cable installation and Transport, lorry >32t, EURO5 (from prod. site to harbour, 1000 km)			
Transport, single unit truck, gasoline powered/US	11636.00	tkm	SimaPro
Lorry 40t/RER/I U	0.00	unit	
Maintenance, lorry 40t/CH/I U	0.00	unit	
Road/CH/I U	0.00	ma	
Operation, maintenance, road/CH/I U	0.00	ma	
Excavation, hydraulic digger/RER U	57.80	m3	SimaPro
Building, hall, steel construction/CH/I U	0.18	m2	SimaPro
Building, multi-storey/RER/I U 7	7.05	m3	SimaPro
Disposal, lorry 40t/CH/I U	0.00	unit	
Disposal, road/RER/I U	0.00	ma	
cable decommission			
Transport, lorry >32t, EURO5 (from harbour to treatment, 1000 km)			
Transport, single unit truck, gasoline powered/US	11636.00	tkm	
Lorry 40t/RER/I U	0.00	unit	
Maintenance, lorry 40t/CH/I U	0.00	unit	
Road/CH/I U	0.00	ma	
Operation, maintenance, road/CH/I U	0.00	ma	
Excavation, hydraulic digger/RER U	57.80	m3	SimaPro
Building, hall, steel construction/CH/I U	0.18	m2	SimaPro
Building, multi-storey/RER/I U 7	7.05	m3	SimaPro
Decommission			
Disposal, lorry 40t/CH/I U	0.00	unit	
Disposal, road/RER/I U	0.00	ma	
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	0.07	t	SimaPro
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH U	0.07	t	SimaPro
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U	0.07	t	SimaPro
Landfill of ferro metals EU-27	11.50	t	

Appendix D: Metadata analysis of previous MW-level wind turbine LCA

Table D-1 Metadata of MW-level wind turbine LCA

Authors	Year of study	Location	Operational/conceptual	Onshore(1)/Offshore(0)	Rated power(MW)	Hub height (m)	Blade diameter (m)	Water depth (m)	Distance from shore (km)	Lifespan (yrs)	Average wind speed at hub height (m/s)	Full load hours (capacity factor)	Scope	Analysis approach	Yearly Energy generation(MWh)	Energy payback time(months)(prim/wind/12)	Energy intensity(MWh prim / 1 Mwhe wind)	GWP(g CO2e / 1kWh wind)	acidification(mg SO2e / kWhe)
Weinzettel et al.	2007			0	5	100	116	100-300	50	20		53%	MTCGOD			13	0.054	11.51	0.14
Guezuraga, Zauner, and Pölz	2010	Austria		1	1.8	65	70			20	6	20.80%	MTCGOD			7.7	0.032	8.82	
Guezuraga, Zauner, and Pölz	2010	Austria		1	2	105	90			20	7.4	34%	MTCGOD			7.8	0.033	9.73	
Tremeac and Meunier	2008				4.5	124	113			20		30%	MTCOD			6.96	0.08	15.8	
Vestas, V112, PE	2009				3	84				20		42.90%	MTCGOD			8	0.034	7	0.28
Wagner et al.	2009				5			30	60	20		44.52%	MTCGOD			32.76	0.137	31.84	
Dirk Hartmann	1996	Germany	O		1	55	54			20		18.50%	MCO					14	
Dirk Hartmann	1996	Germany	O		1	55	54			20		18.50%	MCO					22	

Wiese and Kaltschmitt	1996	Germany	C		1	50	60			20		36.20%	MCO				0.035	10	
Brown and Ulgiati	2000	Italy	O		2.5								MCO				0.13	36.15	
Pehnt M.	2006	Germany	O	1	1.5								MTCOD				0.033	11	0.61
Pehnt M.	2006	Germany	O	0	2.5								MTCOD				0.031	9	0.5
R.H. crawford	2009	Australia		1	3	80	90			20		33.00%			8672	35.43	0.148	32	
Dolan, S. L.	2007	USA			1.8	80	80		0.8	20	6.98	30.00%			4734			24	0.2
Dones, R., C. et. Al.	2007	Europe			2	60	80			20		30.00%			5256		0.571	12.3	0.045
Jungbluth N. et. Al.	2005	Baltic Sea Denmark	O		2	60	80	3 to 5		20		30.00%						13	
Proops, John L. R. et. Al.	1996	UK	O	1	6.6					20		29.00%			16767			34.63	0.27
Rule, B. M., et. Al.	2009	New Zealand	O	1	1.7					100		38.87%			309000		0.0195	3	
Vattenfall	2010	Europe	O		2					20		28.70%			1467000		0.055	17	0.051
Voorspools, K. R. et. Al.	2000	Belgium		0	1					20		34.00%					0.033	9	
Vestas V90	2006	Denmark	O	1	3					20		54.16%	MTCGOD	P			0.0273	4.64	0.114

Vestas V90	2006	Denmark	O	0	3					20		54.16%	MTCGOD	P	1423000	6.8	0.0285	5.23	0.095
Vestas and Elsam	2002	Denmark	C	0	2	60				20		46.46%	MTCGOD	P		9	0.0283	7.62	
Birkeland	2011	Denmark	C	0	5	95	120			20		34.00%	MTCGOD	P				20.6	
SimaPro by Bauer and Burger, PSI	2007	Denmark	O	0	2					20		30.00%	MTCGOD	P			0.0456	12.2	
Min GWP of This study	2012											48.80%						18.68	
Max GWP of this study	2012											49.80%						33.53	

Chapter 4
Characterization and Valuation of Viewshed Impacts of Offshore Wind Farm Siting

Abstract

The purpose of this study was to develop an analytical method to evaluate the external costs associated with the visual impact from offshore wind farm (OWF) siting, considering in contexts of multiple objectives with respect to maximizing energy generation, reducing installation cost, and minimizing social cost. Twenty OWF scenarios in the locations ranging from a distance of 5km to 30km from the shore in four candidate areas of Michigan's Great Lakes are analyzed. Geographic information system (GIS) was used to evaluate the viewshed and then calculate willingness to pay for avoiding visual impact as part of social cost. Next, the social cost of the visual impact is compared to a cost model of site-related installation costs. Finally, an integrated assessment expressed in terms of an energy cost metric is used to identify the best siting scenario. The difference in aggregated cost per unit of generated electricity varies from 0.318 to 1.521 cents/kWh for the studied OWF scenarios. Furthermore, the best OWF scenario with the least cost per generated energy is not always located farthest offshore. These findings suggest that policy makers need to reconsider renewable siting policy in order to effectively promote its development and conciliate the possible opposition from local communities.

4-1 Introduction

The geographical variation in wind resource plays an important role in wind farm siting decisions. High wind speed sites found in the less resistant areas such as mountain ranges, plain fields, and open coastal areas, are desirable locations for large scale wind power facilities due to their generation potential. However, the selection of wind farm sites is complicated by several factors: a) as more and more wind farms are connected to power grids, additional power control on the electricity voltage and power capacity is required to compensate for the fluctuation and unreliability of wind power; and b) excellent wind resource locations are limited and competitive; c) remote and inferior areas increase the transmission lines cost and electricity loss; and d) some possible wind farm locations face community objections, as a result of wind turbine impacts in viewshed, vibration, noise or wildlife.

Offshore wind power faces even larger development challenges than other renewable energy sources, since the unprecedented turbine size and installation farther from shore cause the uncertain benefit and cost for siting strategies. The primary siting objective is to harness the best wind resources in order to minimize generation cost. Wind generation is positively correlated to the distance from shore because the wind speed is faster and steadier. Locating OWF farther offshore also offers the benefit of reducing viewshed impacts as they are less visible from shore. Although the benefits from greater wind energy generation and reduced viewshed impacts are not linearly correlated to the distance offshore, both can be categorized as positive-gain factors as siting distance from shore for OWF increases.

These positive-gain factors are offset by negative-gain factors such as foundation and transmission line costs. About 14-21% of investment cost [85], [86], [12] of wind farm is related to foundation cost, which is mainly a function of the water depth. Since water depth generally increases with distance from coast, micrositing wind farms farther offshore generates higher investment cost. A similar phenomenon occurs with respect to transmission line cost--the further from shore, the more expensive the initial costs.

When all these positive- and negative-gain factors are well presented, an optimal microsite (measured in terms of distance from the shore) can be determined. This work fills a gap among other studies that failed to consider these tradeoffs. The study can provide a methodology for the comparison of wind farm development among candidate areas.

Several offshore wind projects are proposed in the Great Lake areas of Michigan, but the conflict among objectives are an obstacle to development. The concern about the visual impact, property value, and OWF cost have prompted some lawmakers to suggest prohibiting wind turbines in Michigan’s Great Lakes [87]. The lack of available information quantifying the visual impact not only impedes the possible negotiation of alternatives for impacted residents and wind project developers, but also stops the development of offshore wind technologies.

4-2 Literature Review

Wind farm siting is shaped by several factors, some of which are common to both offshore and land-based wind farms. Common siting criteria include wind energy resource availability, transmission capacity, ecological impacts on wildlife, and aesthetic concerns [5],[21],[26]. Many of the findings from land-based wind farm research relevant to these issues can be applied to OWFs, but other challenges such as concerns about noise, vibration, and flick impacts; and the availability of roads infrastructure for wind farm construction and maintenance [21] are not applicable to OWFs. The unique challenges to OWFs include turbine foundation, onsite assembling difficulties, transmission lines under water, inclement weather impacting maintenance and operation, and impacts on aquatic ecosystems and fisheries [88],[27].

Current studies related to the siting of renewables are mainly focused on investigating the maximum renewable energy potential in areas without fully considering environmental constraints [89],[90],[91]. Although these studies quantify the theoretical maximum energy output based on certain types of generators and resource potential in a geographical range, the installed renewable energy systems have fallen short of the predicted potential. This shortage can be attributed, in part, to the lack of the supportive infrastructures and public acceptance. Supportive infrastructures, mainly transmission lines and reserved power capacities, are indispensable for the integration of utility-scale wind farms to the grid due to their role in transmitting generated wind power and balancing the fluctuating in energy when wind farm generation is insufficient.[5] The financial cost of new transmission lines for OWF is substantial especially since it is often dedicated to and paid by the wind farm project alone. In addition, local communities may oppose OWF projects, even in the proposal phase, because of the concerns about viewshed, noise, vibrations, and impact on wildlife. Previous work has simulates the possible effects of integrating renewable energy generation into the electricity system [92], [93]. However, the location specific characteristics of the connected wind farms such as wind speed intensity and stability, transmission line availability, community acceptance, or environmental variations are not considered. These limitations limit the insights from land based wind farms that can be applied to OWFs.

Gap in previous studies is the lack of micro-scale information that can be used to decide the OWF locations within a particular area. OWF siting needs to demonstrate optimal results for the minor change of locational variables, such as the distance of OWFs from the coast or an array of wind turbines. The existing OWF research of macro- or large-scale siting tended to only model energy generation potential rather than to consider the influence of locational variables on the expected objectives, such as energy generation and public acceptance.[94],[95],[96]. Therefore, the best wind potential areas (wind map) as one of the siting references remain too general to help decide OWF location precisely. Some evaluation criteria don’t even include spatial information for siting reference. For example, although public acceptance research about viewshed analysis or WTP reveal the approximate opinions of local communities through simulated seascape photos and questionnaires [97],[17],[15], the lack of scenario comparisons of minor locational changes, and insufficient information on quantitative social costs make the decision on selecting OWF location difficult.

4-3 Contribution and Research Questions

One contribution of this study is to evaluate visual impact as a social cost by developing a method to quantify it in monetary terms. The method identifies the visually impacted areas, calculates the population who reside in these areas, and finally, aggregates external cost of visual impact by the method of calculating their willingness to pay for moving wind turbines farther from shore. This differs from other qualitative and non-spatial visual impact research methods[16], [98]. Expressing these social cost results of OWF visual impacts in monetary terms makes it easier to compare tradeoffs with other objectives such as maximizing energy generation and minimizing installation costs including transmission line costs thus allowing stakeholders to be well informed when making siting decisions. Evaluating these trade-offs also helps to inform the formulation of wind energy policy. Current renewable energy promotion based on either suggested favorable wind resource zones or financial incentives for generated electricity can be reconsidered to encourage proposed projects accounting for social costs once they are better quantified.

This study can help to find the optimal OWF location in a local geographical area while balancing energy generation, installation costs, and social acceptance. Siting OWFs farther offshore not only increases wind energy generation, but may also increase installation costs and reduce visual impacts on coastal residents. To identify the optimal location of OWFs in terms of distance from shore, the developed method examines scenarios with incremental distances offshore and quantifies the trade-offs of expected goals.

The following research questions are addressed: 1) How does one characterize visual impact of OWFs as social cost in monetary terms? 2) What are the costs and benefits of OWFs at different distances from shore? 3) How does one evaluate the optimal wind farm location considering trade-offs of multiple objectives?

4-4 Methods

In this section, the methods used to quantify energy generation, installation cost, and social costs based on OWF site are described. In Section 4-4-1, the data collected for further analysis are described. Section 4-4-2 describes the measurement of WTP to estimate the external cost of visual impact. Section 4-4-3 describes how the installation costs vary with change of site selection. Finally, the theoretical wind energy generation for different OWF scenarios is detailed in Section 4.4.

4-4-1. Data

Data required for this study include Michigan topography, Great Lakes bathymetry, wind speed, wind turbine specifications, local population, land cover, and willingness to pay for avoiding visual impact.

The topology was derived from U.S. Geological Survey 1/3 arc-second (approximately 10 x 10 meter resolution) National Elevation Dataset. Great Lakes bathymetry was acquired from National Oceanic and Atmospheric Administration. The wind speed was from AWS Truewind. The wind turbine specification came from Vestas 3.0 MW offshore wind turbine series.

Population data at census block group level were obtained from the 2010 U.S. census. The land cover data was obtained from National Land Cover Database 2006 (NLCD2006). State, federal and trust (The Nature Conservancy) land boundaries in digital format as well as land and mineral ownership by Department of Natural Resources were collected from the Center for Geographic Information, Michigan. Residents' WTP for moving OWF farther offshore was extrapolated from a questionnaire survey in the Delaware by Krueger, 2007.[99]

Twenty OWF siting scenarios are examined in this study. Each OWF scenario is composed of 100 Vestas 3MW wind turbines arrayed in a 10 x 10 matrix originated to the east. They are assumed to be located in four counties of Michigan at a distance of 5km, 10km, 15km, 20km and 30km offshore. The incremental distances are measured along the shortest distance between wind turbines and the coastline.

4-4-2. Use WTP to measure visual impact as external cost

To quantify the external cost of OWF, the visual impact of wind turbines is firstly defined by considering visually impacted areas, people living in these areas and equivalent monetary external cost estimated that residents have to endure. The external cost of visual impact is transferred from Delaware's study, the detailed calculation of values can be found in Appendixes E. By using the results, the total external cost of visual impact for an OWF in this study is then given by the following expression:

$$f = \sum_i A_i \rho_i \omega_i \qquad (1)$$

where A_i is the visually impacted areas [m^2], ρ_i is the inhabited population density for the mapping area [people/m^2], and ω_i is the monetized external cost of visual impact for wind turbines [\$/person]. The details of each item are described in the following sections.

4-4-2-1. Viewshed impact calculation

The elevation data of wind turbines are firstly added to the DEM base map to represent the 155 meter height of 100 x 3.0 MW wind turbines. The viewshed function in the ArcInfo 10 is then utilized to identify the areas from where the offshore wind farm can be seen. The earth curvature is accounted for in these viewshed assessments, but obstructions from buildings and trees are not considered. The results of visually impacted areas can then be expressed by A_i which is an equation of three variables.

$$A_i = f(h,d,l)b_i \qquad b_i \in (1,0) \qquad (2)$$

where *h* is the turbine height, fixed here at 155 meters, measured from average lake water level to the tip of turbine blades; *d* is the shortest, straight line distance between an OWF and the coast, and varies from 5km, 10km, 15km, 20km, and 30km in each analyzed scenario; *l* refers to the four candidate OWF development areas, including offshore lake areas in Huron, Oceana, Ottawa and Berrien County in Michigan. The value of b_i equals to 1 or 0 indicating if the OWF is visible or invisible from *i* location (Figure 4-1).

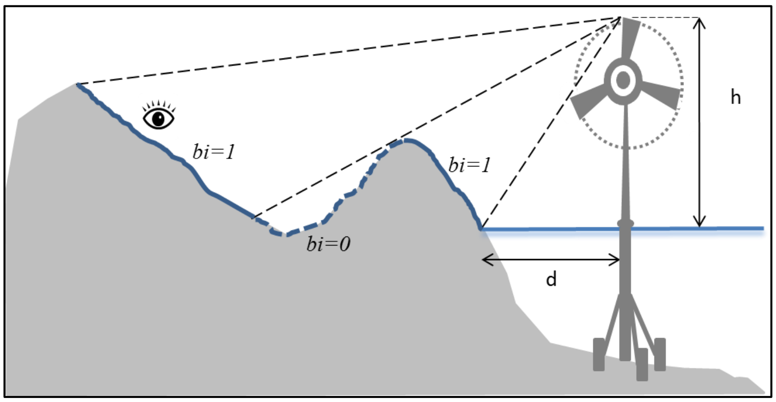


Figure 4-1 Viewshed of wind turbines

4-4-2-2. Generating surface models of population using Dasymetric mapping

The accuracy of population distribution on the surface varies with the mapping methods. Choropleth mapping (maps that use graded differences in shading or color or the placing of symbols inside defined areas in order to indicate the average values of some property or quantity in those areas [100]) of population density is one of widely adopted methods due to its simplicity by dividing by the population in the corresponding spatial unit. However, significant variation in population at finer spatial units will lead to misinterpretation for calculating visual impact in terms of the population. The Dasymetric mapping method adopted in this study can effectively decrease this inaccuracy since population density of finer spatial units can be shown after excluding the uninhabited regions and weighting the relative population density on various land use types.

Four steps are required for Dasymetric mapping of population density in this study. First, inside the coverage of each census block group *k*, uninhabited areas that are excluded from population mapping are categorized into three groups by 1) ownership (State, federal and trust land), 2) land cover (water, wetland, and barren areas) and 3) slopes larger than 15% and located in forest and shrub land areas. Except for the excluded areas, other land cover types j are considered for population mapping. These inhabited areas (the number of raster cells) are calculated and denoted as N_{jk}. Next, population density weighting M_j is based on percentage of impervious surface (Table 4-1). Finally, population density f_{jk} of an approximately 10 x 10 meter raster-based map can be generated in terms of the following formula:

$$\rho_i \in f_{jk}(M,N,P) = \frac{M_j}{\sum\sum M_j N_{jk}} P_k \qquad (3)$$

where P_k is the population amount in block group k.

Table 4-1 Relative population density weighting based on land cover and impervious surface

Land cover types	Open Water, Barren, Wetlands	Herbaceous, Planted/Cultivated	Forest, Shrub/Scrub	Developed, Open Space	Developed, Low Density	Developed, Medium Density	Developed, High Density
Relative population density	0	1	2	4	7	13	18

Note: Classification is based on National Land Cover Database 2006 (NLCD2006)

4-4-2-3. Environmental benefit transfer

The non-market benefit of lakescape requires a valuation technique that describes the aesthetic problem of OWFs facing wind farm developers and local communities. Contingent valuation used in the questionnaire of Delaware’s development of OWFs [15] provides a solid source for transferring seascape value in the case of the Great Lakes of Michigan. Delaware’s study reveals people’s attitude toward OWFs in North America. It also provides reference value information by using willingness to pay for moving wind turbines farther offshore at different distances. A simplified valuation function is transferred from study site (Delaware) to policy site (Michigan) considering the location of communities and the distance from OWFs.

To evaluate external cost of visual disamenity ω, the following expression is assumed:

$$\omega_{MI}(R,d) = f_{DE}(R,d) \qquad (4)$$

where R is the distance of communities from the coast classified into 1 km, 1-7 km and 7-50 km inland, and d is the distance between OWFs and coast, starting from 0 km to 50 km (representing invisible distance). $f_{DE}(R,d)$ is the external cost of visual impact based on the Delaware study based on distance offshore (see Appendix E). The external cost of visual impact is measured in terms of present value in 2010 of 20 years (lifespan of wind farm) of monthly costs.

4-4-3. Measuring installation costs related to locational variation

The initial investment costs of OWFs include the cost of the wind turbines, foundation, collection system, integration system, transmission system, regulation devices, and monitoring and general control [101]. However, in order to highlight the variables that significantly affect the selection of wind farm locations, we emphasize the importance of siting-related variables, which are foundation cost and transmission line cost. These costs are measured as present value of year 2010.

The foundation cost is based on the study of Dicorato et al. [102], which provides a general model that is validated with real costs to measure the investment cost of OWFs. After changing original Euros into U.S. dollars with 1.4 exchange rate (the average rate in 2010), foundation cost C_z expressed as in the Dicorato study is now transformed as follows:

$$C_z = 1.5 \cdot n_{WT} \cdot c_z$$
$$c_z = 1.4 \times 320 \times G_{WT}(1+0.02(D-8))(1+0.8 \cdot 10^{-6}(h \cdot (\frac{\phi}{2})^2 - 10^5)) \quad (5)$$

where n_{WT} is the number of wind turbines, given by 100 for 300MW OWF; c_z is the foundation cost for each wind turbine, [k$/turbine]; The constant 1.5 stands for the additional costs for transport and installation; G_{WT} is the rated power of each wind turbine, given by 3[MW]; D is the lake depth, [m]; h is Hub height, given by 155[m]; ϕ is rotor diameter, given by 110[m].

The transmission line cost assumes that only submarine high voltage cables and the land-based underground lines are designed for the studied 300MW OWFs. A 630-mm^2 150kV cable hence connects the OWF to the nearest existing transmission lines. The total transmission line cost is expressed by following equation:

$$C_{TS} = n_{HV}(c_{m,HV} + c_{i,HV})d_{wf} + n_{HV}c_{uc,HV}d_{ps} \quad (6)$$

where n_{HV} is the number of high voltage lines, given by 1; $c_{m,HV}$ is unit cost of submarine HV cable, given by 938[$/km]; $c_{i,HV}$ is cable transport and installation cost, given by 1008[$/km]; d_{wf}

is the average distance of the OWF from the coast, [km]; $c_{uc,HV}$ is the cost of underground land-based lines, given by 2240[k$/km]; d_{ps} is the nearest length of onshore connection to the main transmission system, [km].

4-4-4. Estimating wind power generation by the Weibull distribution

Wind power generation of each OWF scenario increases with wind speed, which is generally faster when measured far away from the coast because the water surface is relatively smooth. Wind speed also varies by changes in vertical wind shear. To estimate the wind speeds at higher heights from known wind speeds at lower height, a power law is applied to calculate wind speeds at 100 meter hub height from the estimated average wind speed at 90 meters by AWS Truwind. The transformation of vertical wind-speed profile is based on the equation [103]:

$$\nu_{\mathrm{h}}(h) = \nu_{\mathrm{h}_0} \times \left(\frac{h}{h_0} \right)^{\alpha} \qquad (7)$$

where $V_h(h)$ is velocity of the wind at height h, [m/s]; V_0 is velocity of the wind at height h_0, [m/s]; a is the Hellman exponent, given by locational characteristics.

To calculate wind speed patterns, the Weibull distribution is applied by plugging in two parameters, the average wind speed at 100 meter height for scale parameter and the predicted shape parameter based on the results of Chapter 2. Next, the technical specifications of the Vestas 3MW wind turbine are considered. This turbine has a power curve with a cut-in wind speed of 3.5 m/s, nameplate power generation at wind speeds of 12.5 m/s, and a cut-out wind speed of 25 m/s. By combining the wind speed pattern and the wind turbine power curve, the wind energy generation at different wind speeds from Vestas wind turbines can be estimated to demonstrate the total energy generation of each wind farm scenario.

4-5 Results

4-5-1. Visually impacted areas and population

The visual impact caused by installed OWFs can be quantified based on visually impacted population and areas (urban areas are defined as developed areas based on NLCD 2006). Among the four areas studied, the Huron scenarios are the most vulnerable in terms of impacted areas (Figure 4-2). For the Huron scenarios with OWF located 5km from the coast, wind turbines are theoretically visible from more than 1200 square kilometers on shore (including impacted rural and urban areas). However, if only impacted urban areas are considered, the Ottawa scenarios have more visual interference from wind farms. This result is shown in Figure 4-3.

The scenario that causes the most residents to be visually impacted is not completely consistent with the scenarios that visually impact the most area. This implies the importance of metric selection for OWF siting decisions. For example, although the Huron scenarios have a larger visually impacted area compared to both Ottawa and Berrien scenarios, fewer people are visually affected. On the other hand, by comparing scenarios with OWFs at the same distance from coast, the Ottawa scenario results in more visually impacted people than other counties. The visually impacted population may be significantly different. For example, siting wind farms 5km offshore in the Ottawa versus Oceana would lead to a 10 folds increase in impacted population.

Another interesting finding is the relationship between visual impact and the distance of OWFs from the shore. Surprisingly, it is not always true that increasing the distance between wind farms and local communities decreases visual impact. On the contrary, visual impact increases as the wind farm moves farther away in some situations. For example, comparing the 5km scenario to 10km scenario in Berrien areas, the impacted areas and population both increase with distance offshore.

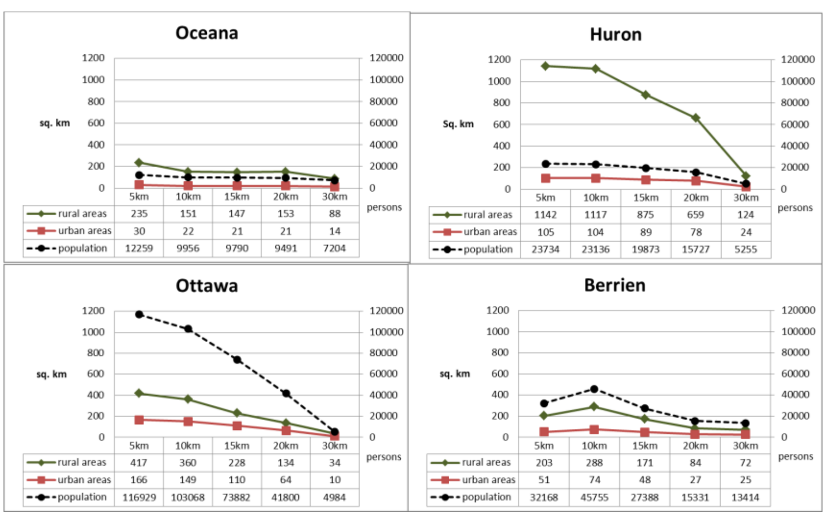


Figure 4-2 Visually impacted areas and population by OWF

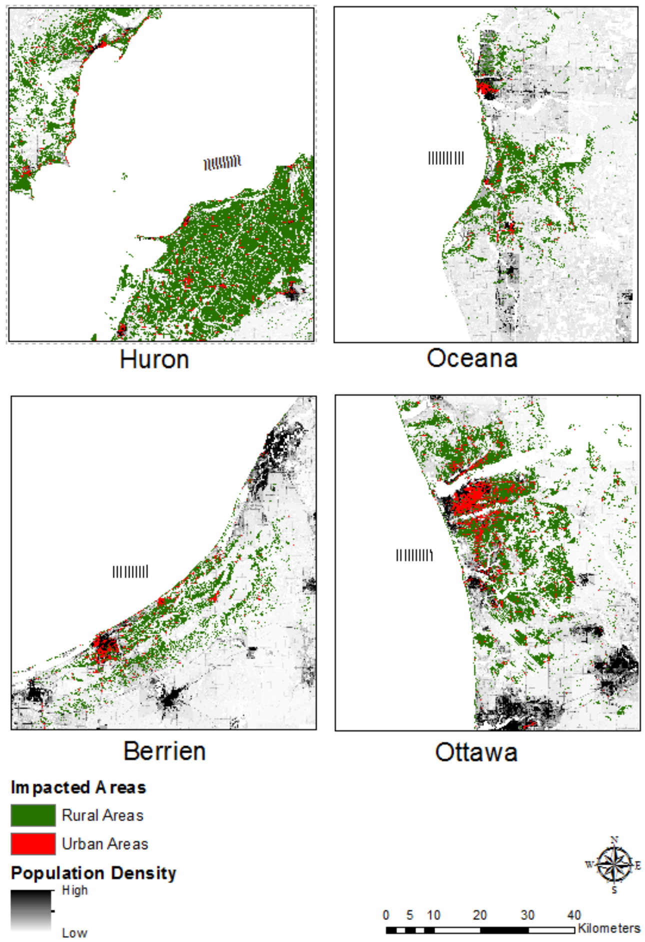
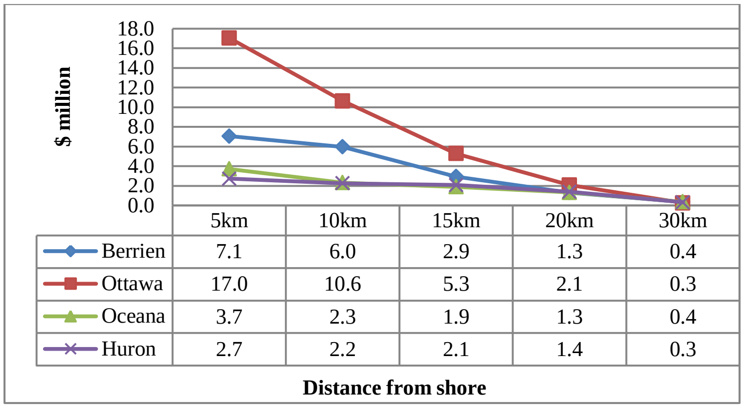


Figure 4-3 Visually impacted areas and population by 5km OWFs in four studied counties

4-5-2. Visual impact of wind turbines as external cost

The external cost of the visual impact from wind farm projects serves as an index for social acceptance and can be represented in the form of monetary units based on the calculation in Equation (1). Comparing the present value of these external costs over a 20 year OWF lifespan shows the cost decreases with the increased distance from the coast (Figure 4-4). But the marginal decreases in external costs per distance interval are not the same among all studied areas. The largest reduction of marginal external costs per kilometer can be found between the 5 km and 15 km scenarios in the Ottawa, followed by Berrien scenarios from 10km to 15km, and Ottawa scenarios from 15km to 20km. If attention is paid to total external costs, the Huron and Oceana scenarios have higher potential for social acceptance at almost all distances with only minor cost differences among them.

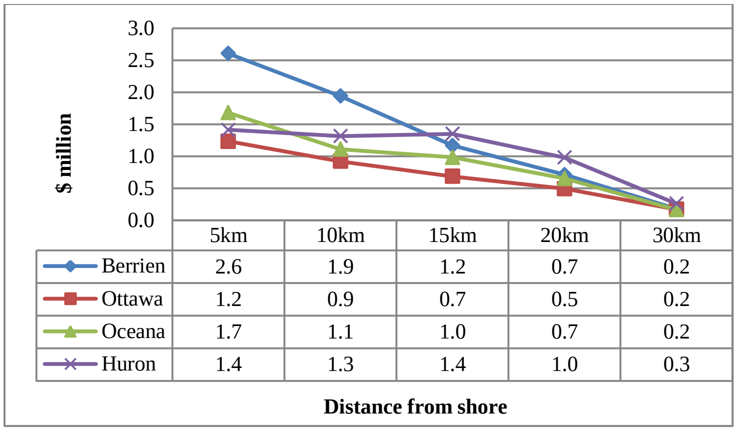
The primary reason for high external cost of visual impact for Ottawa scenarios is that more residents are visually impacted and they live closer to the proposed wind turbine locations. Compared to the scenarios in other counties, the densely populated urban areas in the coastal Ottawa lead to higher social cost. On the contrary, the smallest external cost is found in the Huron scenarios even though the plain topography results in the largest visually impacted area. This is offset, however, by the fact that fewer people are visually impacted by wind turbines due to a smaller population in the county.



	5km	10km	15km	20km	30km
Berrien	7.1	6.0	2.9	1.3	0.4
Ottawa	17.0	10.6	5.3	2.1	0.3
Oceana	3.7	2.3	1.9	1.3	0.4
Huron	2.7	2.2	2.1	1.4	0.3

Figure 4-4 External cost of OWF visual impact in 20 year lifespan

The external cost of OWF visual impact has the most effect on the people who live within 1 km from the coastline. These results were calculated for the different communities (Figure 4-5). If the 5 km and 10 km OWF scenarios are compared for four counties, the external cost for residents within 1km from the coast is highest in Berrien County. For OWFs sited beyond 15 km, the Huron scenarios are expected to show more opposition from coastal residents. In Huron and Oceana Counties more than 50% of external cost from visual impacts comes from coastal residents.



	5km	10km	15km	20km	30km
Berrien	2.6	1.9	1.2	0.7	0.2
Ottawa	1.2	0.9	0.7	0.5	0.2
Oceana	1.7	1.1	1.0	0.7	0.2
Huron	1.4	1.3	1.4	1.0	0.3

Figure 4-5 External cost of OWF visual impact for 1km Coastal Areas

4-5-3. Installation cost based on location

Installation costs based on site location are shown in Figure 4-6. Foundation costs, as well as offshore and land-based transmission line costs are aggregated to represent the site-related installation costs based on equations (5) and (6). The aggregated costs gradually increase as OWF are sited farther offshore because the cost of the required foundation types increase with distance (Figure 4-6). The installation costs of the Huron scenarios are more than five times higher than that of the other locations at the same distances from coast due to the need for longer transmission lines. In the Huron scenarios, the distance of the required land-based transmission line is 100 km, but only 25km in Ottawa and 3km in Berrien and Oceana.

While land-based transmission line costs dominated the installation costs in the Huron scenarios, the cost composition is different in the Ottawa, Oceana and Berrien scenarios where foundation costs dominate. The variation in foundation costs also differ among county areas. In the Oceana scenarios, the foundation cost difference is $72 million. This value is two times larger than the $36 million range in the Huron scenarios. This is an indication that the bathymetric profiles in Oceana waters change more dramatically than that in Huron.

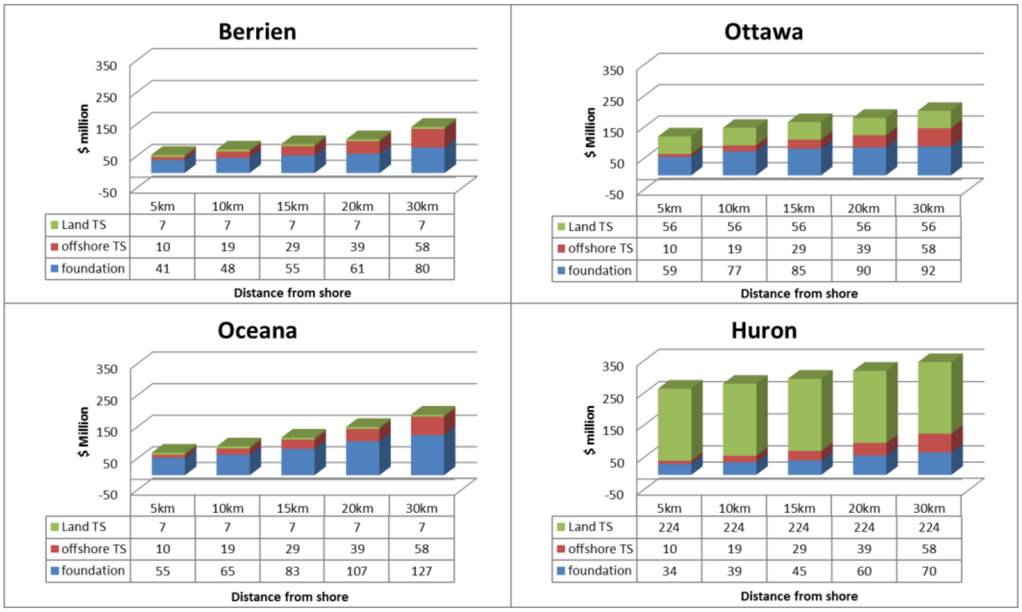


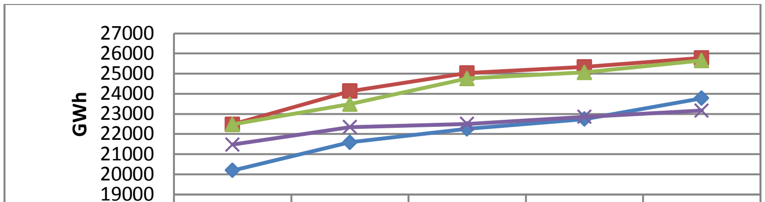
Figure 4-6 Installation cost consist of foundation, offshore and land-based transmission lines

4-5-4. Electricity output and unit cost

The electricity output from wind energy is estimated by equation (7), the wind pattern, and power curve. It considers the average wind speed of the specific location at the turbine height and the wind turbine efficiency. The initial investments costs can be dividend to calculate the cost per unit of electricity generated.

4-5-4-1. Electricity output

The electricity output of siting scenarios at various distances offshore for the four candidate areas is presented (Figure 4-7). The electricity output increases offshore distance with the maximum output being 1.4 times higher than the minimum. Comparing the results at the same distance from shore constant, it is evident the Oceana and Ottawa Counties have better wind resources than the Huron and Berrien Counties.



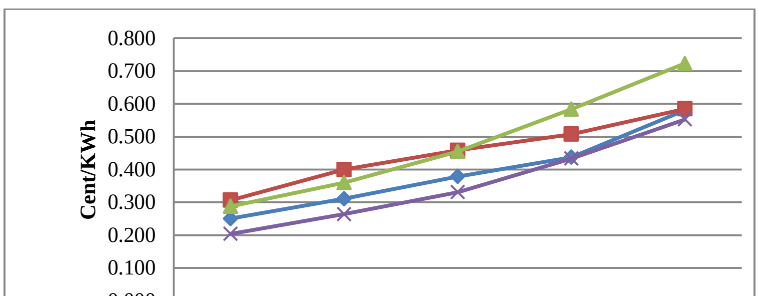
	5km	10km	15km	20km	30km
Berrien	20194	21588	22256	22746	23778
Ottawa	22478	24132	25028	25332	25776
Oceana	22478	23486	24756	25060	25654
Huron	21476	22348	22508	22858	23166

Distance from shore

Figure 4-7 20-year electricity output

4-5-4-2. Change of electricity unit cost for different siting scenarios

Four sets of results showing the change in costs per kWh for each siting scenario are provided in Figure 4-8, Figure 4-9, Figure 4-10 and Figure 4-11. Foundation costs and offshore transmission line costs are shown in Figure 4-8. The variation in costs is more significant within a county area than between county areas. In other words, scenarios located at different distances offshore in the same area vary more significantly than those located at the same distance offshore but in different areas. For example, consider an OWF located 5km offshore in the Huron area. Locating this OWF at 30km offshore would be more costly than locating it at 5km offshore in Ottawa.

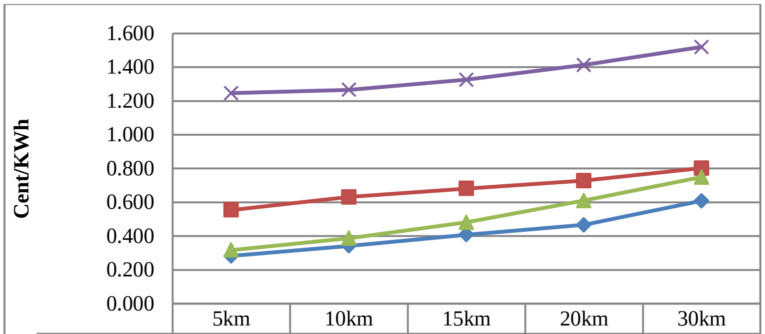


	5km	10km	15km	20km	30km
Berrien	0.250	0.311	0.379	0.437	0.581
Ottawa	0.306	0.399	0.458	0.507	0.585
Oceana	0.287	0.360	0.455	0.584	0.723
Huron	0.203	0.264	0.330	0.433	0.552

Distance from shore

Figure 4-8 Foundation and offshore transmission line cost per electricity output

Land-based transmission line costs are another consideration influencing the implementation of wind power integration. When this cost is introduced into decision making, the results change significantly. Berrien County becomes the lowest cost region and Huron is the highest at every distance from shore (Figure 4-9).

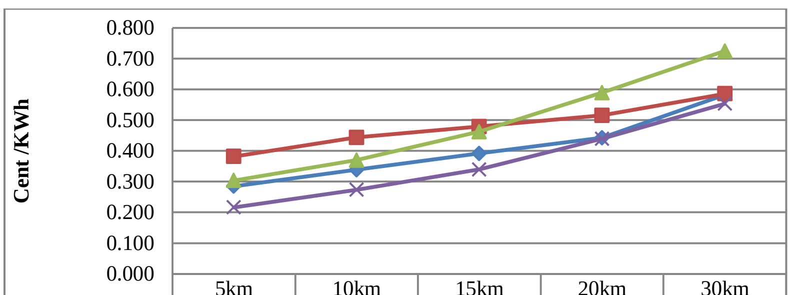


	5km	10km	15km	20km	30km
Berrien	0.283	0.342	0.409	0.467	0.609
Ottawa	0.555	0.632	0.682	0.728	0.802
Oceana	0.317	0.388	0.482	0.611	0.749
Huron	1.247	1.266	1.326	1.413	1.519

Distance from shore

Figure 4-9 Foundation and transmission line cost per electricity output

In order to understand scenarios where onshore transmission costs are born by transmission system operators instead of an individual wind project developer, onshore transmission costs can be excluded from the electricity cost results. Figure 4-10 shows the results based on the external cost of visual impact, foundation cost, and offshore transmission line cost. Compared to installation costs only case shown in Figure 4-8, the relative electricity costs similar since installation costs are more significant. This also means that the increase in installation costs from moving farther offshore outweighs the benefit of decreased visual impact and increased wind energy generation.

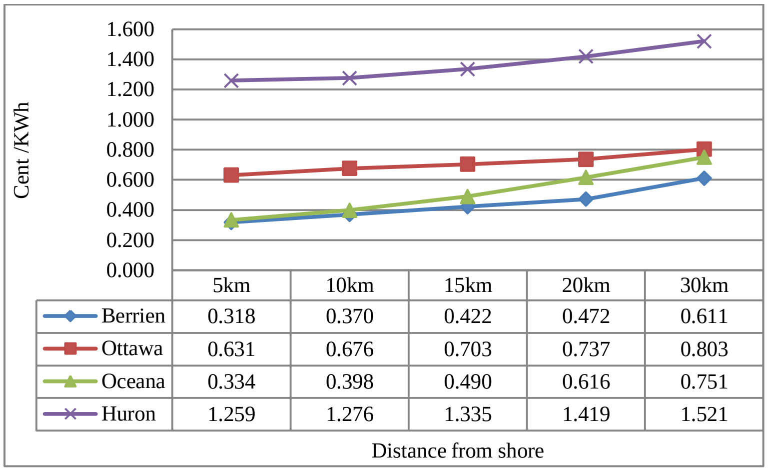


	5km	10km	15km	20km	30km
Berrien	0.285	0.338	0.392	0.443	0.582
Ottawa	0.382	0.444	0.479	0.516	0.586
Oceana	0.304	0.370	0.463	0.589	0.725
Huron	0.216	0.274	0.340	0.439	0.554

Distance from shore

Figure 4-10 Energy cost considering foundation cost, offshore transmission line cost and external cost of visual impact

The electricity cost results based on all considered costs including foundation cost, offshore transmission lines, land-based transmission lines and the external cost of visual impact is shown in Figure 4-11. The trend of increased energy costs along with distance offshore is evened out. The result reflects the fact that land-based transmission line cost, though not as influential as foundation cost and external cost of visual impact on changing the relative energy cost performance along with offshore distance, plays an important role in deciding OWF location at the macro-scale level (between counties) due to its significant difference among county areas.

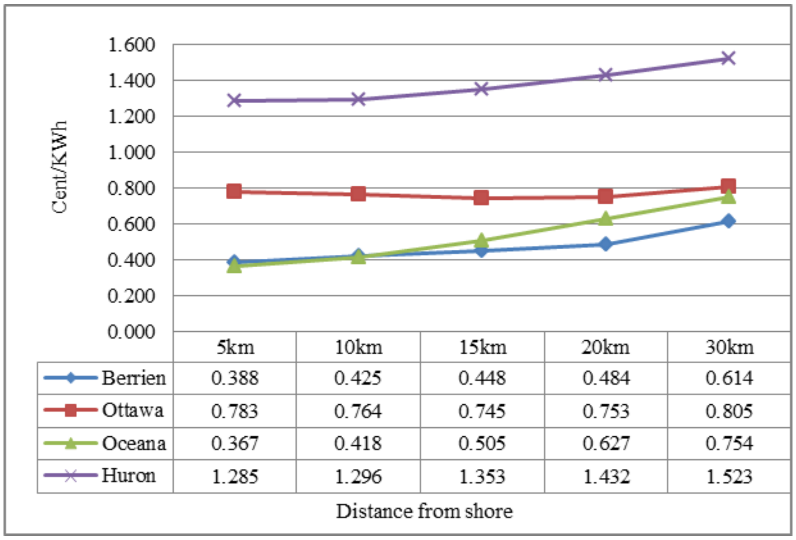


	5km	10km	15km	20km	30km
Berrien	0.318	0.370	0.422	0.472	0.611
Ottawa	0.631	0.676	0.703	0.737	0.803
Oceana	0.334	0.398	0.490	0.616	0.751
Huron	1.259	1.276	1.335	1.419	1.521

Figure 4-11 Electricity cost considering foundation cost, offshore and land-based transmission line costs, and external cost of visual impact.

4-5-4-3. Break-even analysis of external cost of visual impact on wind farm siting

The break-even analysis of wind energy costs shows that the Berrien scenarios are the most sensitive to the change of external cost of visual impact. As the external cost of visual impact increases three-fold, the trend of energy costs for Ottawa scenarios differs from the baseline results. As shown in Figure 4-12, the best energy cost scenario in the Ottawa area is no longer the one closest to coast but the one 15 km offshore. Other assessed wind farm scenarios elsewhere are less affected by increased external cost of visual impact. In Berrien, Oceana and Huron areas, the best energy cost scenario that includes sit-relevant costs and external cost of visual impact remains those closest to the coast.



	5km	10km	15km	20km	30km
Berrien	0.388	0.425	0.448	0.484	0.614
Ottawa	0.783	0.764	0.745	0.753	0.805
Oceana	0.367	0.418	0.505	0.627	0.754
Huron	1.285	1.296	1.353	1.432	1.523

Figure 4-12 Energy cost for external cost of visual impact increased by three times

4-6 Discussion

4-6-1. Visual impact valuation

The external cost of negative visual impacts from OWF development is derived from WTP in this research. The calculation of these viewshed impacts in the research scenarios presented demonstrated that the amount of visually impacted area, the number of visually impacted residents, and the external costs are not always negatively correlated with OWF distance from coast. Instead, in the case of Berrien, moving an OWF location from 5 km to 10 km offshore impacts a larger area and more residents. In the case of the OWF 10 km from shore, it is likely that the high hills close to the coast do not block the view of the turbines for the northern urban areas of the county.

Coastal proximity also plays a role in influencing the external costs associated with negative visual impacts. The coastal area surrounding the Huron Bay area causes the 15km OWF scenario to have higher monetized external costs than scenarios closer to the coast. Although this result only happens for the calculation of people who reside in 1km coastal area, their strong attitude toward lakescape preservation and concern about property values tends to formulate strong objections to OWF development and also influence other people elsewhere.

The percentage of people who reside close to the coast is also a very vital factor influencing the difference in the monetized external cost and the impacted population upon which different siting decisions may be made. An example of this difference can be seen by comparing Berrien and Ottawa scenarios. Due to the fact that there are more urbanized areas close to the coast, in Berrien County, the impacted population of Ottawa 5km OWF scenario is 3.6 times more than that of Berrien's, but the external cost of Ottawa's 5km OWF scenario is only 2.5 times more than that of Berrien's. Choosing monetary or impacted population as the siting criteria in this case can hence result in different siting decision.

4-6-2. Selection of optimal OWF location based on site-related costs

The location of OWFs can have a direct impact on costs associated with the foundations, offshore transmission lines, and land-based transmission lines. These costs are considered in the research scenarios. The results show that Huron, one of the most favorable wind resource zones suggested by Michigan Great Lakes Wind Council, is very costly for OWF development due to the need for long distance land-based transmission lines even though its foundation cost is relatively competitive when compared to the other three studied areas in western Michigan. A renewable energy policy promoting the development of OWFs in these wind resource development areas can be shortsighted by excluding this dominant cost component.

OWF developers cannot compete with fossil fuel-based utilities unless the cost of new transmission lines is the responsibility of Regional Transmission Organizations (RTO)/Independent System Operators (ISO). However, in the situation, the expense of newly added transmission line capacity will likely be transferred to end customers resulting in high electricity cost. As a result of higher energy costs, OWF development may be hindered.

Except for land-based transmission line costs, cost variation of micrositing OWF in one small geographic area is highly affected by OWF's distance from shore. Moving OWF farther from the coast increases total cost due to the need for longer offshore transmission lines and more expensive foundations needed in deeper water. However, more attention should be paid to the trade-offs between these increased costs and the decreased external costs associated with negative visual impacts. If foundation cost, offshore transmission line costs, and higher external costs (i.e. three folds) are aggregated, the least energy cost scenario with respect to OWF distance offshore is neither the closest nor farthest from shore, but rather one in between in

Ottawa County. This approach is useful in informing developers and local communities about the tradeoffs associated with OWF installations, and also provide guidance on siting policy.

4-6-3. Locations with the best wind resources are not necessary optimal OWF sites

Ratio of cost to energy generation is better than wind potential as a siting index

In western Michigan, locations in the lake farther from the coast have generally had better wind potential. But wind resource potential is definitely not suitable as the only indicator for siting decisions. For example, siting OWFs based on wind energy generation would favor the farthest over the closest locations. Simultaneously considering macrositing and micrositing strategies in response to the tradeoffs among energy generation, installation costs, and external costs may be necessary for identifying locations with the lowest costs per unit of electricity generated.

For micrositing decisions, a cost/energy indicator is used to elucidate trade-offs among energy generation, visual impact and installation costs when OWFs are moved offshore. This study demonstrates that the best micrositing strategy is dependent on location. In general, installing OWFs at the nearest distance from the coast may leads to the best outcome. But moderate distances from the coast is even better for Ottawa scenarios when external costs are three times higher than the baseline scenario. Based on the cost/energy information, OWF developers can propose the most profitable location considering the financial compensation paid for external cost of visual impact.

External cost of visual impact needs to be included in the siting decision

One of the motivating factors for deciding OWF locations based on maximizing energy generation in the US is that the primary policy mechanisms (including tax breaks from Federal government and Renewable Portfolio Standard (RPS) from states) are designed to promote wind energy mainly based on energy generation. Government incentives based on generation tend to encourage developers to locate OWFs based on the difference of energy revenue, subsidy and installation costs, but this excludes the potential social cost caused by visual impact. Although the sitting decisions will not necessarily change by including external cost of visual impact according to twenty baseline siting scenarios, it could alter decisions if external costs grow larger (Figure 4-12).

The assumption of a high external cost of visual impact in the break-even analysis is not unrealistic. The original questionnaire survey in the Delaware study assesses the *ex ante* WTP for avoiding visual impact. But the *ex post facto* impact of a wind farm may be higher. Besides the constraint from the dynamic WTP for avoiding visual impact, the impacts of OWFs scenarios are probably affected by the changing population. For example, only around 30,000 residents are visually impacted by the wind turbines in the Berrien 5km scenario. If OWFs are installed in intensely populated areas, the increase in external cost would make it more advantageous to site further from shore.

Moreover, the site-related costs are important component in determining the profitability of an OWF project. The site-related costs in the studied scenarios range from 0.318 to 1.521 cent per generated kWh. Given that the market price for electricity generated by wind ranged from 2.5 to 5.5 cent/kWh in 2007 (the prices are suppressed by the receipt of any available state and federal incentives), the values in this study are 6-61% of the market price [104]. Therefore, understanding site-related costs can be helpful in siting OWFs and increasing their economic feasibility.

4-7 Conclusions

Negative viewshed impacts, one of the most discussed social obstacles related to OWF development is elucidated by the analytical approach taken to quantify its external cost in this research. By evaluating, the quantitative indicators of viewshed impact, presented in terms of impacted area, impacted population, and monetary cost, it was found that moving OWFs farther offshore is in general good at reducing visual impact, but not enough to offset the increased installation costs. In addition, social cost and installation costs are considered along with energy generation to comprehensively assess multiple objectives for siting OWFs at four proposed county areas in the Great Lakes. The results suggest that both macro-siting and micro-siting factors are important considerations in wind farm deployment. The siting scenarios with the lowest energy costs are generally close to the coast. However, if the external cost from negative visual impacts is very significant, the optimal OWF location might be at moderate distance from the coast.

When considering multiple objectives, the cost per unit of electricity in the twenty studied scenarios varied considerably. This result has implications for the current renewable energy policy. First, the most favorable wind resource development areas suggested by Michigan Great Lakes Wind Council may misdirect OWF investment because the rule-based environmental constraints and wind-resource-potential-only planning approaches fail to express the possible opposition from local communities and trade-offs among multiple objectives. Second, micrositing OWF at a moderate distance from the shore is probably beneficial for all stakeholders. A "win-win" situation for utility developers and local communities may be achieved by reducing the external cost from negative visual impacts for the local community as well as reducing installation cost for developers if an appropriate amount of financial compensation is provided to communities. This compensation should be above the community's WTP for avoiding visual impacts, but less than increase in installation costs. This policy mechanism should be carefully considered by policy makers in order to accelerate the development of the wind energy industry.

Several limitations of the study should be mentioned. The methods of environmental value transfer are used to estimate the external cost of visual impact in study site (Delaware) and applying them to the policy site (Michigan). This approach is susceptible to generalization errors.

One such type of error arises from flaws in the primary research. The original questionnaire survey on resident's WTP in Delaware may not have been able to reflect the "real" lakescape value because the values in the study are based on hypothetical wind farms. Other factors such as the effect of weather conditions on visibility, relative landscapes contrast, as well as visual acuity and blade spin are not fully considered either. Moreover, in the viewshed modeling, calculation of visibility only from the elevation data is a simplified approach. By excluding surface objects such as buildings and trees from the elevation information, the visibility of offshore wind farms is over estimated, thus potentially overstating the social cost.

Another limitation of the study is associated with the correspondence between the study site and policy site. Residents in Michigan might be different from people in Delaware in terms of education, religion, ethnicity or other socio–economic characteristics that affect their preference for offshore wind farms. The potential difference in benefits from new jobs associated with the wind industry or shared ownership of wind farms for residents may lead to difference in the WTP of residents in the two states. Hence, decision makers should consider these generalization errors when applying the result of this study.

Another source of uncertainty is related to the composition of the sample in the Deleware study. Only the WTP of permanent residents who would be "directly and continuously" influenced by wind farms are measured in the study. WTP of temporary visitors or occasionally visually impacted residents are excluded from calculation. As a result, the total social cost caused by visual impact of offshore wind farms may be understated. Therefore, the results of this study could be treated as a lower bound because temporary visitors occasionally impacted are excluded. Further field surveys may be conducted to include the perception of tourists about the visual impacts of OWFs. Surveys can also be conducted as part of validation research in candidate areas of Michigan by providing simulated lakescape photos for subjects to describe their WTP for avoiding visual impact.

Finally, one of the missing, site-related criteria that deserve more attention for OWF siting is the temporal coincidence between wind energy supply and load center. The evaluation of OWF siting then may have to consider more diversified criteria, such as the costs and benefits from integrating OWFs into the grid due to saved capacity, displaced fuels, and the reduced air pollution.

Appendix E: Environmental benefit transfer from Delaware to Michigan on visual disamenity of offshore wind farm

The purpose of Krueger's research is to estimate the interest of Delaware residents on offshore wind farms compared to a new coal-fired power plant. The survey is designed in four sections, including attitudes and opinions concerning wind power and the possibility of having offshore wind power in Delaware, choice experiment for preference of offshore wind farm scenarios, beach use, and demographics. A total of 949 surveys were returned, representing 52% of the response rate. Since the results of a choice experiment is applied and transformed to our research, the focus is thus put on explaining the processes.

The survey of a choice experiment was organized by changing hypothetical wind farms (a total of 450 MW wind power project with 500 turbines each 440 feet high) along the coast of the Delaware, with a combination of five various attributes: wind farm location (ocean, bay, inland); distance from coast (0.9, 3.6, 6, 9, 12, 15 and 20 miles); renewable payment ($1, $2 or $8 million); royalty fund (Beach Nourishment Fund, Delaware Green Energy Fund or Delaware General Fund); and, renewable energy fee on monthly electricity bills for 3 years ($0, $1, $5, $10, $20, $30). Paying attention to the distance from coast, residents prefer to pay more for locating wind farms farther offshore comparing to a wind farm 0.9 miles offshore as the baseline (Table E-1). The results also reveal that people living in the ocean areas compared to bay and inland areas are willing to pay more for moving the same distance of offshore wind farm away from coast. This means higher cost of visual disamenity and more utility gained by moving wind farm farther for coastal area residents.

Table E-1 Willingness to pay ($/month for 3 years) to move wind turbines from a baseline of 0.9 miles to 3.6, 6, 9, 12, 15, or 20 miles offshore (Table 7.6 from [99])

Distance(miles)	Inland	Bay	ocean
3.6	$9.38	$16.62	$40.83
6	$12.84	$22.74	$55.87
9	$15.58	$27.60	$67.81
12	$17.53	$31.05	$76.28
15	$19.04	$33.72	$82.85
20	$20.98	$37.17	$91.33

To evaluate the social cost of visual disamenity from offshore wind farms at different location, Krueger's research on WTP to move wind turbine offshore is used to define and represent the cost variation. The total WTP for moving wind turbines from 0 km to 50 km (about 31 miles) is defined as total social cost of visual disamenity, because this is the maximum amount of price that people will pay in order to make wind turbines invisible at a farther distance from coast. Part of the social cost unwillingly paid by the residents is then defined as external cost; that is the social cost subtracted by willingness to pay of moving wind turbines from coast. Since the WTP of visual disamenity in Krueger's research is based on the comparison between a baseline OWF scenario located 0.9 miles offshore and other scenarios located in various distance offshore, the WTP of moving OWFs from 0 mile to 0.9 mile is missing. Therefore, an extrapolation is used by calculating the marginal WTP/mile from 3.6 miles to 6 miles, i.e. ocean area residents will like to pay 0.9 miles * ($55.87 - $40.83) / (6 miles – 3.6 miles) = $5.64 in order to move wind turbine from 0 mile to 0.9 mile from coast. Meanwhile, the recalculated data in the tables maintain the heterogeneity of visual disamenities in the population (Figures E-1 to E-3). Residents near coast (< 1km), referred to those previously defined by Krueger's study as Ocean area residents, shows a higher level of concern about the visual impact compared with residents who live farther away from the coast (between 1-7 km and beyond 7 km). This agrees with the findings by Ladenburg and Dubgaard [105] that people using the coastal zone directly compared to others with less connection to the coast generate higher environmental costs if wind turbines are installed there.

Figure E-1 Social cost of visual disamenity for locating offshore wind farms at different distance from coast at area <1km inland

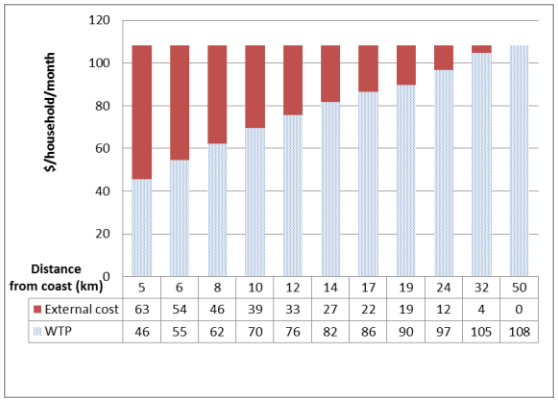


Figure E-2 Social cost of visual disamenity for locating offshore wind farms at different distance from coast at area 1km-7km inland

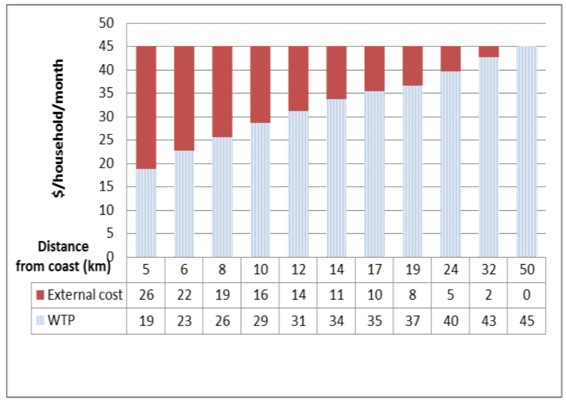


Figure E-3 Social cost of visual disamenity for locating offshore wind farms at different distance from coast at area >7km inland

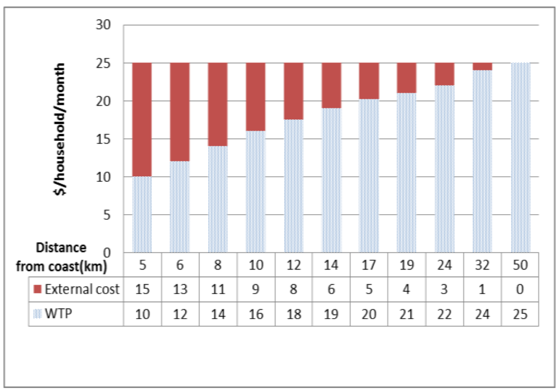
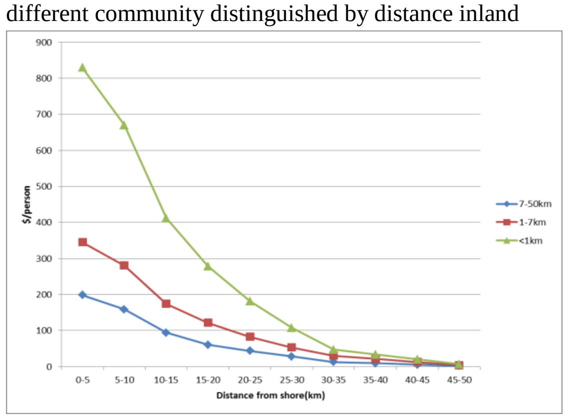


Figure E-4 External cost of visual disamenity for locating offshore wind turbines at certain distance from coast at different community distinguished by distance inland



Following the external cost of visual impact is defined and calculated in the unit of \$/household/month, it is then transformed for the purpose of comparison into the unit of \$/person to show the time value of money and compounding return. Since the original questions asked to respondents in Krueger's survey is "To offset the initial costs of providing wind energy to Delaware residents, assumes that there would be a "Renewable Energy Fee" added each month to your electric bill, for the first three years only", a discounted present value of the 3-year future cash flow is derived from the equation below;

$$NPV = \frac{cpi}{HN} \times \sum_{t=0}^{36} \frac{FV_t}{(1+i)^t}$$

where FV_t is the future value of external cost of visual disamenity in month t; i is the interest rate, 7%/12 is assumed for each month; *cpi* stands for Consumer Price Index, 1.052 is given to transfer 2007 survey to 2010 comparison; *HN* is the household number, 2.58 is given according to U.S. Census Bureau.

Finally, the present value of external cost of visual impact is presented in Figure E-4. It can be expressed as $f_{DE}(R,d)$, which is a function of location *R* (1km, 1-7km and >7km inland) and distance offshore *d*(distance between OWF and coast). The values are then used to multiply the number of Michiganians who can see the turbines from where they live. This transformation of environmental benefits/costs helps us to modeling visual impact for candidate wind farm projects at different distance from coast.

Chapter 5

Multi-objective Analyses of Offshore Wind Farm Siting: An Integrated Assessment of Energy, Economic, Environmental and Social Factors

5-1 Introduction

Identifying locations for installing wind power systems requires consideration of multiple characteristics of each potential location to determine financial feasibility and social acceptance of wind farm developments. Most offshore wind farm (OWF) projects in Michigan and the U.S. remain at a planning stage and face challenges for energy, economic, environmental and social reasons. From the perspective of maximizing the overall net benefits to society, a successful OWF in a marine or lacustrine area needs to account for multiple objectives as well as policies that influence the value of wind power.

The purpose of this study is to examine the benefits and costs for an offshore wind farm with regard to energy, economic, environmental and social objectives. The analysis of benefits and costs will include criteria, such as wind energy generation and installation costs, as well as externality criteria such as avoided pollution and monetized visual impact. The integrated assessment of each scenario is expected to provide a reference point for siting OWFs and for designing policies aimed at promoting renewable energy.

The objectives of this study are to:

- examine the performance of an offshore wind farm with respect to multiple objectives;
- understand the change of benefits and costs in multiple objectives as offshore wind farm locations change;

- analyze the trade-offs of multiple objectives for different OWF siting scenarios. The results of this analysis can be used to improve on incentive policies that aim only at maximizing potential of wind energy production;
- compare the influence of preferences and values on the total resulting performance of siting scenarios;
- examine the significance of the environmental externality on wind project development using the life cycle pollutant emissions and displaced pollution; and
- develop a Pareto efficient frontier for OWF siting objectives.

To achieve the goals of the study, several research questions are addressed. How are the objectives associated with energy, economy, environment and visual amenity affected for OWF alternatives by installation at different distances offshore and in four different counties? How will the weighting methods in a multi-criteria decision analysis (MCDA) influence the result of evaluation on siting scenarios? One of the criteria for evaluating wind farm projects is examining the environmental benefits of avoided pollution from burning fossil fuel. How does this metric influence the resulting performance of siting scenarios?

5-2 Background

5-2-1. Offshore wind farms complicate human-environment systems in coastal areas

Offshore wind farms are a new type of resource use in coastal areas that potentially place new pressures on current human-environment interactions. The multi-faceted impacts of OWFs at various spatial and temporal scales may require reconciliation of conflicting objectives among stakeholders and decision-makers related to wind, land, water, and resources, as well as the different attitudes and concerns of interest groups toward OWF development. The difficulty of responding to these impacts is compounded by the uncertainty of data on operational OWFs, the continuous improvement of wind power technologies, and social-economic changes. Therefore, an important aspect of any solution to the intricate OWF siting problems in coastal areas is an integrated approach that combines interdisciplinary knowledge and addresses relevant policy issues.

One integrated assessment method is called the DPSIR framework [106], which stands for drivers, pressure, state, impact and response, and can be used to analyze causal relationships for the OWF development in the coastal area. The pressure on developing wind farms in coastal areas is driven by forces that can be characterized as natural, social, and political. First, in response to fossil fuel scarcity and global climate change, wind power is recognized as an important alternative energy source, due to its renewable and low carbon characteristics. Offshore wind power is often better than comparable onshore systems for meeting the energy goals because of the steadier and stronger wind resources found offshore. In addition, OWFs are advantageous because they provide for energy diversification for the sake of national security, reduction in transmission losses due to their closeness to load centers, and reduced objections from local communities relative to land-based wind farm projects. Finally, policies at the federal and state levels provide economic incentives for the future growth of OWFs. The federal production tax break for wind energy is a policy that significantly decreases the financial cost of wind power. For example, the Renewable Energy Standard for the State of Michigan requires electricity providers to develop a retail supply portfolio that includes at least ten percent renewable energy by 2015. These policies directly influence the current future developments of OWFs.

OWF development faces multiple barriers. Some of the barriers are technical in nature, such as the difficulty of installing the foundation for a wind turbine in deeper water, the need for greater capacity and upgrade of transmission power grids, and the goal of maintaining the stability of a power supply for an interconnected power system. Other barriers may be related to markets. For example, the current electricity market may need to be redesigned to accommodate non-conventional power generators, especially given the intermittent nature of wind. In addition, time-consuming approval processes introduce administrative barriers involving a variety of institutions. Part of the reasons for the administrative barriers is the competition among various resource uses in coastal areas. This increases the administrative efforts to deal with multiple, often conflicting interests. Finally, the feasible waters for OWF development provide not only a wealth of wind resources but also a number of current uses, such as for shipping lanes, cultural resources like shipwrecks, commercial fishing areas, and military operation areas.

The impact of OWFs on coastal areas varies across a number of thematic dimensions. Positive impacts include their contributions to a diversified and cleaner electricity supply that can reduce GHG emissions and to job opportunities supporting the manufacture of wind turbine components. On the other hand, negative ecological impacts include effects on migratory birds, bats, and aquatic life that may be influenced by the construction and operation of OWFs [107]. The magnitude of positive and negative impacts depends on where wind farms are sited. Meanwhile, the relative importance of these various impacts is affected by the attitudes and concerns of diverse stakeholder groups, including the preferences, interests and cultural values of local communities, who play an important role in determining the political success of wind farm projects. For example, different attitudes toward OWFs affect how the visual impact of wind turbines is evaluated. Sometimes these attitudes are very dynamic, perhaps changing over time as the wind farm is in operation or the wind project benefits are shared by local communities.

The various driving forces, barriers, and impacts of OWFs combine to create different effects on human-environment interactions in the coastal areas. These effects might be reflected in behavioral change by individual and institutions, altered investment decisions, and modified policy and management approaches. For example, some county governments have already banned the planning of OWFs in western Michigan's waters of the Great Lakes[87]. Some OWF developers adapt investment decisions to OWF locations based on economically viable foundation types [2],[106]. Below, I illustrate the state-level policies and management responses to OWF development opportunities in the coastal areas with the example of Wind Energy Resource Zones and the expedited transmission line siting permission [11].

5-2-2. Policy response to installing OWFs in Michigan coastal areas

Wind Energy Resource Zones (WERZs) are regions identified because of their high potential for wind energy generation[109]. Upgrades or construction of transmission systems that are connected to wind farms in these regions are generally required in order to integrate their power with the power grid. WERZs are the response of the Michigan Public Service Commission to the Renewable Energy Standard, which mandates the increase of renewable energy in Michigan to serve its electric needs in the state.

WERZs for land-based wind farms are evaluated through a series of methods, including exclusion criteria, wind speed mapping, wind turbine setback distances and estimation of wind energy production potential. Four WERZs were suggested in a study by the WERZ Board [109]. WERZs were identified and evaluated with regard to wind potential and 22 exclusion criteria. A report issued by Michigan Great Lakes Wind Council identified five favorable offshore Wind Resource areas[110]. They are all larger than 20 contiguous square miles and have water depths of 45 meters or less. The Thumb Region of Michigan (region 4) was identified as the Primary WERZ with the highest wind potential.

Once wind resource zones are identified, several processes can be used to provide incentives for wind power development. One is the expedited application for the siting of transmission lines. This facilitates construction of transmission cables to connect WERZs to the grid. According to the ITC Transmission report, $510 million is required to upgrade the transmission infrastructure to meet the estimated wind energy potential in the Thumb Region of Michigan [111]. Considering the huge investment in transmission infrastructure, the assignment of WERZs requires careful assessment of the benefits associated the choice of wind farm locations.

In the face of the complicated human-environment interactions in coastal areas, implementing policies that would improve the overall outcomes associated with the rapid growth of wind power, which includes 4000MW of wind generation projects in development with Michigan [11], is challenging because maximizing the net benefits of OWFs to society have to consider different interests and trade-offs among multiple objectives. The current WERZ policy aims at locating wind farms in locations with rich wind resource and that are supported by governments and infrastructure investment. However, it is questionable that the optimal result can be reached if the design of WERZ policy does not account for all the benefits and costs associated with a full range of economic, environmental, and social factors.

5-2-3. Literature of integrated assessment and multi-objective decision making

Integrated environmental assessment (IEA) is an evolving approach that incorporates multiple stakeholders and disciplinary perspectives to produce a response to environmental stresses and changes and improve environmental quality at different temporal and spatial scales [112]. Pierce defined IEA as "a process of collecting information about the current and future state of environmental quality and resources, analyzing it, and deciding on actions to optimize the future environmental state and avoid, diminish or remedy environmental harm" in a report produced for the European Environment Agency [113]. Methods that can inform IEA include the aforementioned DPSIR framework [106], life cycle assessment (LCA) [113], and spatial analysis with geographic information system (GIS) [112]. Although DPSIR (illustrated above), LCA, and spatial analysis are all helpful in analyzing the state of various systems and conditions, they are insufficient for weighing tradeoffs, identifying optimal solutions, and engaging stakeholders in making specific decisions. For these reasons, a multiple criteria decision analysis (MCDA) approach is suggested for evaluating stakeholders' preferences on different alternatives according to specific attributes and objectives. Compared to DPSIR, which examines the causes and effects of OWFs in coastal areas [106], MCDA is better at informing the choice among OWF sites in terms of the multiple objectives and the tradeoffs between them.

MCDA can be used to evaluate a set of alternatives based on conflicting and incommensurate criteria [114]. MCDA has been widely used to evaluate the performance of energy supply systems with respect to multiple objectives. Wang et al. reviewed applications of MCDA to energy systems and found that criteria grouped into four general categories: technical, economic, environmental and social [115]. The method is also useful for investigating the impacts of utility location on each of the four categories of criteria. Because of the location dependence, higher costs, and potential CO2 emission reductions associated with renewable energy, identifying optimal locations for renewable energy sites requires investigating multiple objectives. For this reason, MCDA has been used in studies of optimal locations for solar [116], wind [117], and waves [118].

MCDA has also been used in studies of general environmental issues in the energy sector [119]–[122]. Georgopoulou et al. used an MCDA-based model called ELECTRE Tri to study pairwise alternatives with regard to different cost, applicability difficulties, environmental and social impacts for reducing GHG emissions in Greece's energy sector [119]. The analysis was based on the preferences of various actors involved in the decision-making process. Hung et al.

used a fuzzy version of the analytical hierarchy process (AHP) method to translate qualitative objectives of a food waste management system into quantitative objectives [120]. AHP was initially developed by Kaplan and Saaty in the 1990s to evaluate the performance of alternatives against several criteria [122]. AHP, similar to MCDA, is designed to evaluate multiple objectives, but it emphasizes the hierarchical relationship of criteria. Chatzimouratidis and Pilavachi applied the AHP approach to evaluate power plants with regard to their overall impact on the living standard of local communities using technological, economic and sustainability criteria [123]. They defined a hierarchy tree using two main categories: technology/sustainability and economic performance, which were further divided into several subcriteria, including efficiency coefficient, availability, capacity, reserves/production (R/P) ration, capital costs, O&M costs, fuel costs, and external costs.

There remains a number of research gaps associated with the use of MCDA applied to questions in the energy sector. First, even though criteria evaluated for most studies cover a wide range, both negative (i.e. visual interference) and positive (i.e. avoided pollution) impacts of externalities on different stakeholders have not been included in previous studies. Over-simplified criteria against external costs may lead to a bias in the weight assigned to different system characteristics, which can then influence the resulting assessment of energy systems. Another issue is rooted in the difficulty of integrating quantitative and qualitative dimensions. The suitable transformation of criteria into monetary units will make the resulting performance of alternatives more commensurable for integrated analyses.

The results of MCDA studies are significantly influenced by two processes: criteria selection and weighting methods. Several principles have to be followed for selecting criteria [115]. Criteria have to reflect the essential characteristics of evaluated alternatives. They should be used to evaluate the interested objectives. Meanwhile, each criterion has to be measurable, obviously comparable, and independent from other criteria at the same hierarchical level. The weight given to each criterion can be subjectively assigned to indicate decision makers' preferences or objectively calculated to represent the degree of variance and independence of criteria, or by a combination of methods. These weights can have large influence on the outcomes of evaluations.

All the studies discussed above that have used MCDA in renewable energy systems are *a priori* methods that let decision-makers weigh their preferences before the decision process is applied to the objective functions. The main flaw of these methods is that decision-makers are often unable to accurately quantify their preferences beforehand. For example, the visual impact of OWF is difficult to quantify in the planning stage. Hence, some interactive methods or *a posteriori* methods are proposed to adjust *a priori* models. A *posteriori* methods generate Pareto optimal solutions for a problem and then decision-makers select their preferences from them. The difficulty of generating the Pareto optimal front hinders the utilization of *a posteriori* method. In interactive methods, "phases of dialogue with the decision makers are interchanged with phases of calculation and the process usually converges after several iterations to the most preferred solution" [124].

5-2-4. Comparison of Multiple Criteria Decision Analysis and Economic Evaluation Method

The development of wind energy project is characterized by conflicting objectives. To tackle the problem involving more than one objective, MCDA is a useful tool because it can aggregate all the evaluations concerning each criterion/objective into a single index associated with each alternative. The criteria can be measured by either quantitative or qualitative scales. Compared to the economic valuation methods (EVM), MCDA doesn't have to convert each criterion measurement into monetary values. This implies that MCDA can avoid the restrictions and controversies of EVMs. For example, the Contingent Valuation Method (CVM), one of EVMs, does not provide valid valuation when the respondents are not familiar with the goods being measured [125]. Nor does CVM work if respondents believe they are not responsible for the environmental improvement [126].

Another advantage of MCDA is that it has a high level of transparency in the decision making process [127]. The preferences and values of stakeholders on different objectives are expressed in terms of weighting. Therefore, this can encourage the participation of more than one decision maker and support the communication between opposing parties with regard to understanding trade-offs between concerned objectives. For EVMs, the price information of monetization is usually based on average preferences and heterogeneity of different parties is not represented. Consequently, using EVMs are difficult to show the possible disputes between users in the decision making process.

EVMs are more advantageous than MCDA in comparing the evaluation results to other financial investment projects. The evaluation results measured by EVMs can be expressed in terms of net present values considering the discounted benefits and costs over the life time of goods. It is easy for developers, investors, and some people to make decision among options based on their familiarity with monetary units. For this reason, the EVMs mat be more practical to implement.

This research therefore examines and compares the performance of different siting scenarios evaluated by MCDA and EVM. The results can help to understand how different evaluation methods influence the decision making.

5-3 Methods and data

This section discusses each step in the application of MCDA to evaluating 20 OWF locations in Michigan, i.e. attribute selection, objective weighting, and evaluation. The sites are located in the waters of four counties at 5, 10, 15, 20 and 30 km offshore. Each scenario assumes that 100 x 3MW Vestas V112 wind turbines are to be sited and connected to an offshore substation and to the power grid through transmission lines.

5-3-1. Criteria selection

Criteria are defined as including the objectives at which decision makers are aiming (e.g., increasing environmental quality and energy production) and the attributes describing a set of alternatives with respect to those objectives (e.g., distance from shore and amount of wind energy potential). Four objectives were first established as decision goals: energy, economic, environmental, and social objectives. For each objective, one or several criteria are selected and evaluated according to the attributes of the sites to compare sites in terms of the performance of the objectives. The criteria for OWF siting scenarios not only consider the need of financial analyses (i.e. energy generation, installation costs, and renewable energy certificate price) but also the environmental analyses (life-cycle pollution of CO_2 eq, SO_2, NO_x emissions, displaced pollutants, and the external cost of visual impact). In other words, the siting scenario evaluation takes externalities into account. The selected criteria for each objective are described in the following subsections.

5-3-1-1. Criteria for the energy objective

The value of delivered electricity by wind energy is selected as the criterion for the energy objective. First, potential wind energy generation from wind turbines is measured based on 100 x 3MW Vestas wind turbines arrayed in 10 x 10 layout and wind speed profiles estimated for each site using the Weibull distribution with an average wind speed from the NREL wind maps [22] as the scale parameter and predicted *k* extrapolated from Chapter 1 as the shape parameter.

The energy loss of a wind farm was estimated based on turbine availability, wake effects, collection system, and transmission lines. The wind turbine is assumed to be available 8400 hours in a year [128]. The wake effect is a phenomenon that describes the decreased energy generation of a wind turbine due to the wind speed decay caused by other wind turbines. To account for the influence of the wake effect on energy generation of OWFs, a 25% loss of rated wind turbine power is assumed based on Nysted and Horn's study of OWFs in Denmark [129]. For collection and transmission loss, a simplified measure of conductor loss is used (i.e., dielectric, screen, and armor loss are not calculated). The conductor loss [W] then is the product of current [A] squared and resistance [Ω] according to Ohm’s law. The cable resistance is 0.0283 Ohm/km and 0.0446 Ohm/km for the 33kv and 132 kv cables, respectively [130], [131].

The annual amount of energy delivered to the grid was then multiplied by 13.7 cents/kWh to represent the generated revenue. This energy price was the base price of the Cape Wind power purchase agreement (PPA) without including the 5 cents/kWh from the renewable energy certificate (REC) price [6], [10], [132], Cape Wind is the first U.S. offshore wind power project approved and the only available PPA information for U.S. offshore wind power. Finally, the annual energy value is discounted along with a 7% discount rate for 20 years to represent a present value in year 2010.

5-3-1-2. Criteria for the economic objective

The installation cost was selected as the criterion for the economic objective. This study uses an OWF cost model developed by Dicorato et al. [101] to measure the installation cost differences due to the variation of site-related attributes for each alternative. The model includes economic costs in pre-investment and investment stages associated with the costs of the turbine, foundation, collection system, integration system, transmission system, grid interface, and project development in 2010 (see Appendix F).

5-3-1-3. Criteria for the environmental objective

The environmental objective was assessed by three criteria, including net and avoided emissions of CO_2 equivalents (CO_2e), SO_2 and NO_x. Each criterion considers the life-cycle emissions of OWFs as well as the avoided emissions from displaced fossil fuel burning, due to wind energy generation. The measurement of life-cycle CO_2e, SO_2 and NO_x emissions is based on the LCA results in Chapter 2.

The pollutants avoided by wind energy are measured by the emissions of displaced non-baseload electricity. The eGrid datasheet from 2012 is used to represent the pollutant emissions for non-baseload electricity, which is mainly from thermal plants. However, the eGrid data only measure the emissions from fuel consumption. The comprehensive life cycle emissions of electricity should also take into account the fuel-cycle emissions and the emissions for power plant infrastructure. The emissions for different types of power plants and feedstock were gathered from the GREET [133]. Given the generation mix of Michigan, the displaced life-cycle emissions from non-baseload electricity were calculated (Table 5-1).

Table 5-1 Displaced life-cycle emissions from wind energy in Michigan

Emissions	**Infrastructure**	**Feedstock**	**Fuel burning**	**Total life-cycle emission**
CO_2 eq [g/kWh]	0.84	50.24	932.86	983.94
SO_2 [g/kWh]	0.002	0.06	3.33	3.40
NO_x [g/kWh]	0.001	0.11	0.43	0.54

The criteria selected for the environmental objective do not include all pollutant inventories that can potentially cause environmental impacts. The reason is that power plants only report detailed inventory data for certain pollutant emissions. Meanwhile, the lack of regulations on most emissions leads to the lack of market prices for emission allowance permits.

5-3-1-4. Criteria for the social objective

The social objective was assessed by the criterion of visual impact. The attribute score was measured by the method developed in Chapter 4. The locations from where the OWF can be seen are identified and transformed to values representing the number of visually influenced people, based on the population density model. Their willingness to pay for moving wind turbines farther offshore is used to calculate the external cost of visual impact.

5-3-2. Normalization of outcomes

A normalization process was conducted to reclassify the relative importance of siting scenarios to a common scale in each criterion score. The transformations were conducted by the equation

$$N_{ij} = \frac{x_{ij} - x_{minj}}{x_{maxj} - x_{minj}}$$

where N_{ij} is the normalized score for *i*-th siting scenario and the *j*-th objective, x_{ij} is the raw scores, and $x_{\max j} - x_{\min j}$ is the range of maximum and minimum score for the *j*-th objective. The normalized value is between 0 and 1. A higher value represents a relatively better outcome.

5-3-3. Objective weighting

A weight was assigned to each objective to indicate its relative influence on the overall acceptability of an OWF site. Two types of weighting methods were adopted for comparison, including subjective weighting and objective weighting. Six different combinations of weights were given to the four objectives (Table 5-2) to represent the subjective preferences of stylized decision makers. Weighting combination 1 only considers the energy objective. Weighting combination 2 considers financial benefits and costs of OWFs by giving weight to the energy and economic objectives. Weighting combinations 3 and 4 assume a possible compromise among the four concerned objectives and give each objective different weight to evaluate the effects of differences in relative importance. Weighting combination 5 is designed to give the economic objective more weight. Weighting combination 6 gives equal weighting to the four objectives.

Table 5-2 Different weighting on objectives

Weighting type	Weighting composition	Weighting on energy objective	Weighting on economic objective	Weighting on environmental objective	Weighting on social objective
Subjective	W1:Energy only	1	0	0	0
	W2:Prefer energy and economy	0.6	0.4	0	0
	W3:Compromise I	0.4	0.3	0.2	0.1
	W4:Compromise II	0.4	0.4	0.1	0.1
	W5:Cost first	0.4	0.6	0	0
	W6: Equal weighting	0.25	0.25	0.25	0.25
Objective	TOPSIS	0.15	0.17	0.18	0.50

An objective weighting method called TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is introduced to determine the weighting based on the degree of variance from the ideal outcome [134]. The method gives more weight to objectives where all evaluated alternatives have less variation from the ideal alternative. The weighting to each objective can be given by solving the optimal equations below,

$$min \sum_{i=1}^{m} \sum_{j=1}^{n} {w_j}^2 (x_{ij} - {x_j}^*)^2$$

$$\text{s.t.} \sum_{j=1}^{n} w_j = 1, \quad w_j \geq 0$$

where x_{ij} is the outcome for *i*-th alternative of *j*-th objective, ${x_j}^*$ is the best alternative of *j*-th objective, and w_j is the weighting for *j*-th objective.

5-3-4. Monetizing attribute outcome

To compare the environmental and social objectives to the energy and economic objectives in monetary units, I converted these criteria scores. The monetization of the external cost of visual impact is detailed in Chapter 4. The focus here will thus be on the attribute outcome of pollutant budget, which I monetized using four valuation methods: the market price of emission permits; the marginal avoided damage cost of incremental emissions; REC (renewable energy certificate); and joint effect.

The market clearing price for a pollution-allowance permit results from a cap-and-trade regulation. Although the total quantities of pollutants will not be reduced through trading emission permits, some people argue that governments can achieve the goal of reducing the impact of pollution by buying and retiring permits [135]. Therefore, the price of emission permits is a useful estimate of the social costs of displaced pollution. For the CO_2e price, I used the California Carbon Allowances (CCAs) as a reference, which traded for about $15 a ton of CO_2e a year in 2013 [136]. CCA carbon market can thus provide market clearing price information. The SO_2 and NO_x prices are based on the EPA SO_2 and NO_x emission allowance price based on the EPA's Clean Air Interstate Rule (CAIR) and the NO_x Budget Trading Program (NBP), respectively. The 2010 prices were $16.5 and $44.7 per ton, respectively, for annual sulfur dioxide and summer seasonal (May 1 to September 30) nitrogen oxides emission allowances [137].

Another method used to evaluate the externality of pollutant budgets is based on the social cost of pollutants, which estimates the monetized damage associated with an incremental increase in pollutant emissions in a given year [135]. According to the Interagency Working Group on the Social Cost of Carbon, the "central value" (representing the average expected impact) for the social cost of carbon is $21/ton [138]. For the environmental externalities of SO_2 and NO_x, Matthews and Lave reviewed twenty studies and concluded that the mean estimated external costs were $2000 and $2800 per ton of air emissions, respectively in 1992 [139].

The third approach used for estimating the environmental externality of pollution emissions is based on the Renewable Energy Certificate (REC) price. The RECs are the tradable proof of renewable energy generation required by the Renewable Portfolio Standard (RPS) regulations meant to increase the supply of renewable energy. This policy not only supports the development of renewable energy projects, but it is also concretely designed to reduce/displace the pollution of generating electricity from burning fossil fuels. In this approach, the REC value is added to the avoided marginal damaged cost of pollution emissions for the purpose of measuring attribute outcome of OWF scenarios. The REC price is about 5 cent/kWh in the states where RECs are purchased to meet RPS obligations [6], [10].

The last monetization method used to estimate externality of environmental criteria is the variant of the third monetization method. To consider the situation that the amount of capped pollution (SO_2 and NOx) is not reduced with the increased use of wind energy [140]–[142], the potential benefits for each siting scenario are merely selling values of emission permits. For displaced CO2 emissions, the marginal avoided damage cost of CO2 is used to evaluate their environmental benefits, since there is currently no cap-and-trade carbon market in Michigan. The value of RECs is also added in order to jointly represent the effect of environmental objective.

5-3-5. Evaluation

Alternative sites were evaluated for objective performance based on the seven weighting methods and four monetization approaches, which can each be treated as a weighting method. The overall evaluation aggregates the economic benefits and costs across all objectives. The performance ranking of twenty siting scenarios by different weighting methods are pairwise compared to understand their degree of (Spearman) correlation. For example, if the performance rankings of twenty siting alternatives by two weighting methods are exactly the same, their correlation coefficients will be 100%.

To understand how OWF siting is influenced by the contract price of wind energy, a scenario analysis is conducted using a reference price from land-based wind energy projects in Michigan. The weighted average levelized wind energy contract price was provided by Michigan Public Service Commission at 8.032 cent/kWh [143]. Compared to the calculation applying PPA price of Cape Wind, this average contract price can thus be treated as a conservative scenario for calculating the net benefit values for twenty siting alternatives.

Furthermore, a scenario analysis is conducted to reflect the variation of metric values for environmental attributes. The variations are caused by fluctuation of market prices (i.e. REC price or market clearing price for a pollution allowance permit) or the differences of estimation methods (i.e. marginal avoided damage cost of pollutant emissions) (Table 5-3). A low value model and a high value model are compares to the baseline model for twenty alternatives. In the low value model, all lower metric values are used to calculate net benefit values for OWF alternatives. On the other hand, in the high value model, all higher metric values are used to calculate net benefit values for OWF alternatives.

Table 5-3 Different metric values used for calculation of environmental benefits (Values in bold are used for baseline scenarios.)

Variables and units		Value		Data source	
		Low	**High**	**Low**	**High**
Market clearing price for a pollution allowance permit	CO_2 [$/ton/yr]	1.86 - 3.38	**15**	RGGI [144]	California carbon market [136]
	SO_2 [$/ton/yr]	**16.5**	278	U.S. EIA [137]	U.S. EIA [137]
	NO_x [$/ton/yr]	**44.7**	807	U.S. EIA [137]	U.S. EIA [137]
Marginal damage cost of pollutant emissions	CO_2[$/ton]	**21**	65	Interagency Working Group [138]	Interagency Working Group [138]
	SO_2 [$/ton]	970 (in 2007)	**2000** (in 1992)	Muller [145]	Matthews and Lave [139]
	NO_x [$/ton]	200 (in 2007)	**2800** (in 1992)	Muller [145]	Matthews and Lave [139]
RECs	[cent/kWh]	**5**	35	Green power markets where RECs are purchased on a voluntary basis [6]	Compliance markets where RECs are purchased to meet state RPS obligations [6] [146]

5-4 Results and discussion

5-4-1. Performance of siting scenarios from multiple objectives

Differences among the best and worst sites in terms of the various criterion scores are relatively small (Table 5-4). This suggests that determining the optimal OWF sites may need to consider the weighted combination of the criteria and address the trade-offs between objectives. Meanwhile, variations in preferences and values of stakeholders for certain objectives may affect the decisions made for the best siting alternative.

To deal with large differences in the absolute values between criterion outcomes, the normalization process is very helpful in identifying the relative importance of performance of different sites on each objective. Several trends are evident in the results of the normalization process: (1) siting OWFs farther offshore has better wind energy generation (normalization score close to 1); (2) siting OWFs closer to shore has cheaper installation costs; (3) the normalized scores on the social objective have less variation compared to other objectives (Table 5-5 and Figure 5-1).

Table 5-4 The fourteen attribute outcomes of twenty offshore siting scenarios in four different Michigan counties. Bolded values indicate the best and worst outcomes within each attribute.

	Criteria(Objectives and attributes)	Energy Objective	Electricity output potential in 20 years [E+7 MWh]	Lack of turbine availability (energy loss)[MWh]	Wake effect loss [MWh]	Collection system loss [MWh]	Transmission loss [MWh]	Delivered Electricity by 100 Vestaas V112-3.0MW wind turbine in 20 years [E+07 MWh]	Economic objective	Installation cost [$m]	Environmental objective (avoided pollutants)	CO2 eq saving [kton]	SO2 saving [kton]	Nox saving [kton]	Environmental objective (life-cycle impact)	CO2 eq emission [kton CO2 eq]	SO2 emission [kton]	NOx emission [kton]	Social objective	External cost of visual impact [$m]
Berrien	5 km		**2.06**	**8.30**	**48.41**	**0.09**	**0.24**	**1.45**		**930.17**		**14257.87**	**49.26**	**7.79**		604.83	1.09	3.09		7.06
	10 km		2.20	8.87	51.75	0.10	0.44	1.55		988.34		15223.02	52.59	8.32		441.30	1.06	2.16		5.97
	15 km		2.27	9.15	53.35	0.11	0.65	1.59		1046.52		15674.61	54.15	8.57		676.33	1.52	3.12		2.94
	20 km		2.32	9.35	54.53	0.12	0.86	1.63		1104.70		15999.49	55.28	8.74		733.21	1.61	3.59		1.31
	30 km		2.42	9.77	57.00	0.13	1.35	1.70		1221.05		16680.29	57.63	9.12		656.78	1.38	4.03		0.35
Ottawa	5 km		2.29	9.24	53.89	0.11	1.10	1.60		1003.05		15787.15	54.54	8.63		420.55	1.04	1.82		**17.04**
	10 km		2.45	9.92	57.85	0.13	1.48	1.72		1182.89		16918.24	58.45	9.25		574.78	1.29	2.63		10.63
	15 km		2.54	10.29	60.00	0.14	1.82	1.78		1313.09		17517.65	60.52	9.57		595.70	1.31	2.99		5.28
	20 km		2.57	10.41	60.73	0.15	2.09	1.80		1396.09		17704.98	61.17	9.68		616.51	1.34	3.34		2.07
	30 km		**2.62**	**10.59**	**61.79**	0.16	2.65	1.83		1439.20		17963.93	62.06	9.82		657.85	1.38	4.04		**0.25**
Oceana	5 km		2.29	9.24	53.89	0.11	0.29	1.61		953.77		15866.40	54.82	8.67		**419.87**	**1.04**	**1.82**		3.71
	10 km		2.39	9.65	56.30	0.12	0.52	1.68		1085.19		16556.10	57.20	9.05		692.68	1.57	2.90		2.31
	15 km		2.52	10.17	59.35	0.14	0.80	1.77		1143.37		17425.79	60.20	9.52		594.74	1.31	2.98		1.90
	20 km		2.55	10.30	60.08	0.15	1.05	1.79		1346.81		17615.72	60.86	9.63		615.84	1.33	3.34		1.32
	30 km		2.60	10.54	61.50	**0.16**	1.57	**1.83**		**1560.01**		**17982.96**	**62.13**	**9.83**		657.57	1.38	4.04		0.37
Huron	5 km		2.19	8.83	51.48	0.10	3.51	1.51		1122.63		14841.94	51.28	8.11		606.26	1.09	3.09		2.72
	10 km		2.28	9.18	53.57	0.11	3.98	1.57		1157.20		15411.71	53.25	8.42		440.97	1.06	2.15		2.25
	15 km		2.29	9.25	53.96	0.11	4.22	1.58		1238.98		15500.94	53.55	8.47		661.86	1.49	3.08		2.08
	20 km		2.33	9.39	54.80	0.11	4.54	1.60		1248.74		15716.62	54.30	8.59		681.87	1.51	3.42		1.39
	30 km		2.36	9.52	55.53	0.12	**5.06**	1.61		1341.49		15883.70	54.88	8.68		**776.73**	**1.67**	**4.28**		0.31

Table 5-5 Normalization of outcome for each objective across the twenty sites in four Michigan counties. Extreme values in bold.

	Objective	Energy Objective	Economic objective	Environmental objective	Social objective
Berrien	5 km	**0.00**	**1.00**	**0.00**	0.59
	10 km	0.26	0.91	0.46	0.66
	15 km	0.38	0.82	0.40	0.84
	20 km	0.47	0.72	0.42	0.94
	30 km	0.65	0.54	0.57	0.99
Ottawa	5 km	0.41	0.88	0.69	**0.00**
	10 km	0.71	0.60	0.88	0.38
	15 km	0.88	0.39	**1.00**	0.70
	20 km	0.93	0.26	1.00	0.89
	30 km	0.99	0.19	0.96	**1.00**
Oceana	5 km	0.43	0.96	0.71	0.79
	10 km	0.62	0.75	0.70	0.88
	15 km	0.85	0.66	0.97	0.90
	20 km	0.90	0.34	0.97	0.94
	30 km	**1.00**	**0.00**	0.96	0.99
Huron	5 km	0.16	0.69	0.18	0.85
	10 km	0.31	0.64	0.52	0.88
	15 km	0.33	0.51	0.36	0.89
	20 km	0.39	0.49	0.37	0.93
	30 km	0.44	0.35	0.27	1.00

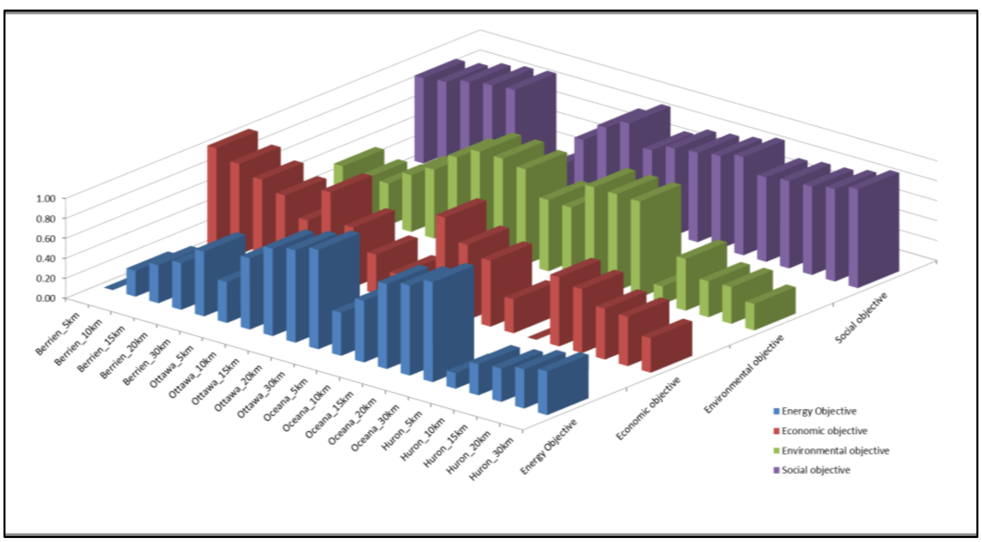


Figure 5-1 Normalization of outcomes for each objective across the twenty siting scenarios in four Michigan counties

5-4-2. Influence of monetization methods on determining OWF locations

All siting scenarios had a positive value for the environmental objective, because the positive environmental externality caused by displaced pollutant emissions from burning fossil fuel predominantly outweighed the negative externality caused by the life-cycle air emissions of the offshore wind farms. However, the aggregate outcome value for environmental objective varied depending on the monetization method used (see Table 5-6). In general, the approach involving multiplying a pollutant budget by “the market clearing price of emission permits” result in the lowest values for all sites, compared to the other three monetization approaches. In comparison, monetizing the outcome of the environmental objective using the “REC price plus marginal avoided damaged cost of air emissions” resulted in the highest values at all sites. By comparing the net benefit values for all sites using the four monetization methods, we find that two siting scenarios are not feasible because they yield negative net benefits, even if a carbon price is included as part of the OWF benefits (M1 approach). However, these two sites became feasible when the OWF benefits were evaluated by including the damaged external cost of air emissions (M2 approach), or the damaged external cost and REC price (M3 and M4 approaches).

Table 5-6 Net dollar value of siting alternatives by four monetization methods. Bold values represent extreme results

County	Distance from shore	Monetization methods for environmental objective			
		M1:Market price of emission permit [$m]	M2:Damaged cost [$m]	M3:REC and avoided damaged cost [$m]	M4: Joint effect [$m]
Berrien	5 km	219.0	342.5	726.3	644.5
	10 km	243.3	381.6	791.3	698.8
	15 km	221.5	357.4	779.3	689.1
	20 km	190.6	327.1	757.8	667.7
	30 km	132.0	274.6	723.6	630.1
Ottawa	5 km	263.9	409.6	834.5	736.5
	10 km	180.6	332.5	787.9	686.3
	15 km	104.4	260.6	732.1	628.0
	20 km	39.6	196.0	672.5	568.8
	30 km	18.9	174.4	657.9	555.5
Oceana	5 km	**333.0**	**479.5**	**906.6**	**808.0**
	10 km	255.2	400.7	846.4	749.3
	15 km	270.0	425.3	894.4	790.9
	20 km	82.4	237.8	712.0	608.8
	30 km	**-100.5**	**55.2**	539.3	436.8
Huron	5 km	78.6	207.9	607.4	521.6
	10 km	93.5	233.8	648.6	554.7
	15 km	15.9	150.4	567.6	478.4
	20 km	24.1	159.1	582.2	493.1
	30 km	-55.3	76.6	**504.2**	**418.1**

Using the REC pricing mechanism within RPS policy can effectively decrease the supply of electricity generated from fossil fuels and thus reduce the pollutant emissions. This benefit is treated as a positive externality gained by the whole society. On the other hand, renewable energy developers can attain the benefits from RECs sold in the market. Therefore, the REC policy is not only beneficial for an environmental objective but also creates benefits for other objectives due to the development of renewable energy, such as energy independence and diversification, job creation, and technology research and development.

Policies designed to control pollutant emissions or develop renewable energy may increase the public good as well as effectively change the selection of an OWF location. A good example of the latter effect is a comparison of the worst location amongst the twenty offshore sites monetized by each of the four different approaches in this study. The worst site measured by the M1 or M2 approaches was the Oceana 30 km scenario, but the worst measured by the M3 and M4 approaches was the Huron 30 km scenario. The reason for this difference is that even though all monetization approaches account for the displaced pollutants from wind energy, the M3 and M4 approaches use a higher positive externality value. This favors of sites that deliver more electricity. Therefore, because OWF development acts as a kind of pressure on coastal environments in the DPSIR framework, and has the potential to change the status and cause impacts to the complicated human-coastal system, any responsive policy that is expected to increase the public good and designed to incentive energy generation should carefully avoid an uneven impact at the local level due to the selection of the OWF location.

The multi-objective analyses of OWF sites in response to different policy regulations are crucial because the different regulations can achieve results that are completely opposite of those intended. No matter what monetization method was adopted, the best and worst (or second worst) siting scenarios were found in Oceana County at the 30 km offshore range (Table 5-6). The Oceana 30 km scenario is the second worst amongst twenty siting scenarios measured by the M3 approach. Moving wind turbines from 5 km to 30 km in Oceana County may cause the value of the siting scenario to drop as much as one half of the best scenario value (M3), or even drop from a positive value to a negative value (M1).

5-4-3. Preferences on different objectives affects the OWF value and location selection

Different weighting methods for four objectives are used to examine the influence of stakeholders' preferences on the OWF siting decision. The first group of weighting methods is called subjective weighting; these are coded as W1 to W6. The highest value amongst the sites in each county area were those located farthest offshore when the energy objective is weighted more, and those located closest to the coast when the economic objective was weighted more (Table 5-7, Table 5-8, Table 5-9 Table 5-10; Figure 5-2, Figure 5-3, Figure 5-4, Figure 5-5).

However, the best-value scenario was located at a moderate distance from shore depending on the trade-offs of energy and economic objectives. For example, the 10 km scenario was the best choice in Huron County for both W2 and W5 weighting methods.

Weighting methods W3, W4 and W6 were created to compare environmental and social objectives with energy and economic objectives in the decision making. Although the weighting distribution for the four objectives is slightly different amongst the three methods, the resulting of the best site in each county was the same. This suggests that the distance from shore for siting an OWF in a given county is not particularly sensitive to the relative weights selected, even if the decision makers express different degrees of concern about visual impacts or the environmental benefits of wind energy.

This TOPSIS method considered the degree of variance of the outcomes and results from the optimal weighting for energy, economic, environmental and social objectives, which was determined to be 16%, 18%, 19% and 47%, respectively. The result of the best site in each county was exactly the same from the TOPSIS methods as from the equal weighting method (W6). This once again supports the argument that, based on the rankings of site results, the OWF siting decisions are relatively insensitive to the weights placed on the four objectives included in the decision.

The results of monetized weighting approaches M1 to M4 are discussed in the section 5-4-2, above. Their comparison with other weighting methods is discussed in the section 5-4-4, below.

Table 5-7 Aggregated score of weighted objectives by different weighting methods (Berrien County), of subjective weighting (W1-W6), objective weighting (TOPSIS), and monetization (M1-M4). Extreme values in bold.

Weighting method (weight on energy objective)	W1 (1)	W2 (0.6)	W3 (0.4)	W4 (0.4)	W5 (0.4)	W6 (0.25)	TOPSIS (0.16)	M1	M2	M3	M4
5km	0.00	0.40	0.46	0.36	0.60	0.40	0.46	0.74	0.68	0.55	0.58
10km	0.26	0.52	0.58	0.53	**0.65**	0.57	0.60	**0.79**	**0.77**	**0.71**	**0.72**
15km	0.38	0.55	0.60	0.56	0.64	0.61	0.68	0.74	0.71	0.68	0.70
20km	0.47	0.57	0.61	0.58	0.62	0.64	0.73	0.67	0.64	0.63	0.64
30km	**0.65**	**0.61**	**0.63**	**0.63**	0.58	**0.69**	**0.78**	0.54	0.52	0.55	0.54

Table 5-8 Aggregated score of weighted objectives by different weighting methods (Ottawa County), of subjective weighting (W1-W6), objective weighting (TOPSIS), and monetization (M1-M4). Extreme values in bold.

Weighting method (weight on energy objective)	W1 (1)	W2 (0.6)	W3 (0.4)	W4 (0.4)	W5 (0.4)	W6 (0.25)	TOPSIS (0.16)	M1	M2	M3	M4
5	0.41	0.60	0.59	0.57	**0.69**	0.50	0.36	**0.84**	**0.84**	**0.82**	**0.82**
10	0.71	0.67	0.65	0.68	0.64	0.64	0.57	0.65	0.65	0.70	0.69
15	0.88	**0.68**	**0.68**	0.74	0.59	0.74	0.73	0.47	0.48	0.57	0.54
20	0.93	0.66	0.66	0.74	0.53	0.77	0.80	0.32	0.33	0.42	0.39
30	**0.99**	0.67	0.67	**0.75**	0.51	**0.79**	**0.84**	0.28	0.28	0.38	0.35

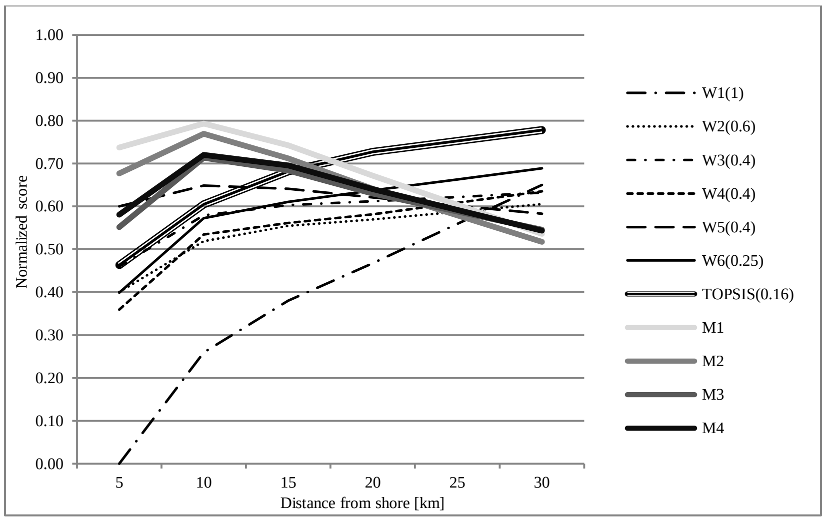


Figure 5-2 Aggregated score of weighted objectives by different weighting methods (Berrien County), of subjective weighting (W1-W6), objective weighting (TOPSIS), and monetization (M1-M4)

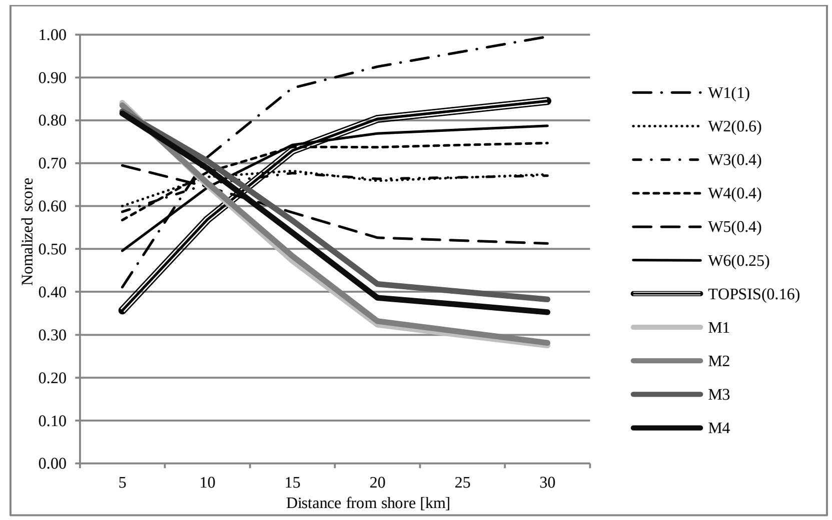


Figure 5-3 Aggregated score of weighted objectives by different weighting methods (Ottawa County), of subjective weighting (W1-W6), objective weighting (TOPSIS), and monetization (M1-M4)

Table 5-9 Aggregated score of weighted objectives by different weighting methods (Oceana County), of subjective weighting (W1-W6), objective weighting (TOPSIS), and monetization (M1-M4). Extreme values in bold.

Weighting method (weight on energy objective)	W1 (1)	W2 (0.6)	W3 (0.4)	W4 (0.4)	W5 (0.4)	W6 (0.25)	TOPSIS (0.16)	M1	M2	M3	M4
5km	0.43	0.64	0.71	0.68	0.75	0.73	0.75	**1.00**	**1.00**	**1.00**	**1.00**
10km	0.62	0.67	0.71	0.70	0.70	0.74	0.78	0.82	0.81	0.85	0.85
15km	0.85	**0.77**	**0.79**	**0.82**	**0.74**	**0.85**	**0.86**	0.85	0.87	0.97	0.96
20km	0.90	0.68	0.69	0.75	0.56	0.79	0.83	0.42	0.43	0.52	0.49
30km	**1.00**	0.60	0.60	0.69	0.40	0.74	0.81	0.00	0.00	0.09	0.05

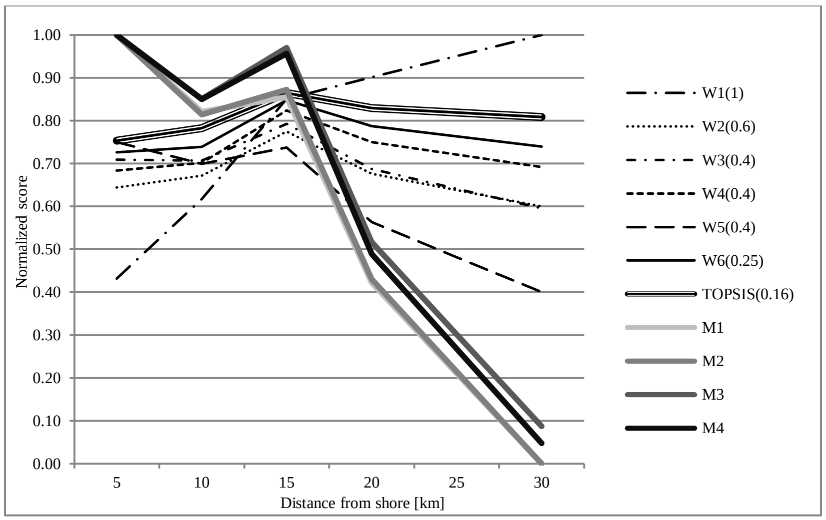


Figure 5-4 Aggregated score of weighted objectives by different weighting methods (Oceana County), of subjective weighting (W1-W6), objective weighting (TOPSIS), and monetization (M1-M4)

Table 5-10 Aggregated score of weighted objectives by different weighting methods (Huron County), of subjective weighting (W1-W6), objective weighting (TOPSIS), and monetization (M1-M4). Extreme values in bold.

Weighting method (weight on energy objective)	W1 (1)	W2 (0.6)	W3 (0.4)	W4 (0.4)	W5 (0.4)	W6 (0.25)	TOPSIS (0.16)	M1	M2	M3	M4
5	0.16	0.37	0.44	0.39	0.48	0.47	0.59	0.41	0.36	0.26	0.27
10	0.31	**0.44**	**0.52**	**0.51**	**0.51**	**0.59**	**0.68**	**0.45**	**0.42**	**0.36**	**0.35**
15	0.33	0.40	0.46	0.45	0.44	0.52	0.63	0.27	0.22	0.16	0.15
20	0.39	0.43	0.48	0.47	0.45	0.55	0.66	0.29	0.24	0.19	0.19
30	**0.44**	0.40	0.44	0.43	0.38	0.51	0.65	0.10	0.05	0.00	0.00

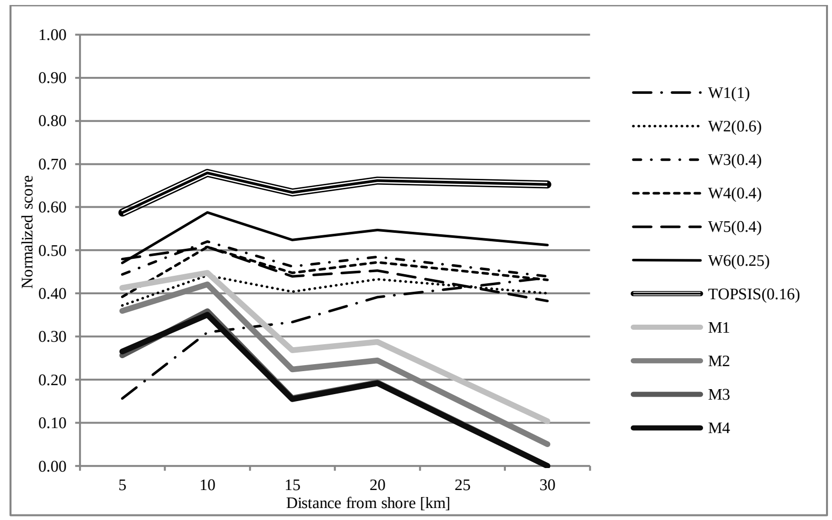


Figure 5-5 Aggregated score of weighted objectives by different weighting methods (Huron County), of subjective weighting (W1-W6), objective weighting (TOPSIS), and monetization (M1-M4)

5-4-4. Evaluating performance rankings of siting scenarios by weighting methods

Eleven different weighting or monetization methods that cause different aggregate effects on the calculated values of twenty OWF sites were compared in a pairwise to evaluate the correlations of site rankings (

Table 5-11). The OWF siting decisions made by different weighting preferences were not consistent in terms of their performance ranking. Among the eleven weighting and monetization methods, W3, which weights energy, economic, environmental, and social objectives as 40%, 40%, 10% and 10%, respectively, tended to be the most representative weighting method as a result of its relative higher correlation with other weighting methods. The W3 weighting method also had the same first-ranked site as W2, W4, W6 and TOPSIS.

When the W1 to W6 and TOPSIS weighting methods were compared to the monetization methods, M1 to M4, the pairwise correlations were very low. The only exception was the W5 weighting method (weight energy objective at 40% and economic objective at 60%), which had nearly a 100% correlation with the M1, M2, M3, and M4 methods. Overall, these results suggest that using monetization methods to decide OWF location will lead to results equivalent to decision making based on only high weights placed on the energy and economic objectives.

Preferences and values on energy, economic, environmental and social objectives expressed in the MCDA method not only comprehensively inform OWF stakeholders and policy makers on how their decisions might potentially affect the already complex coastal environment, but also serve to mediate amongst contradictory perspectives by facilitating understanding about possible siting outcomes from each others' judgments. Our study shows that different preferences and weighting methods can lead to the same outcome on OWF location, but that there are some monetized outcomes can produce results that are quite different from those that treat energy, economic, environmental, and social objectives as relatively equal considerations. These two situations implies that the former might be helpful to reach an agreement for different interest groups facing controversy OWF siting; and the latter that emphasizes the equality of the concerned objectives is at cost of net benefits for the whole society.

Table 5-11 Correlation matrix of rankings by the eleven weighting methods. Numbers in parenthesis indicate which among the first three rankings of sites, were the same under the measurements calculated by the two compared weighting methods.

	W1	W2	W3	W4	W5	W6	TOPSIS	M1	M2	M3	M4
W1 (Energy 100%)	1										
W2 (Energy 60%, economic 40%,)	0.79	1									
W3 (Energy 40%, economic 40%, environmental 10%, social 10%)	0.67	0.94 (1)	1								
W4 (Energy 40%, economic 30%, environmental 20%, social 10%)	0.86	0.97 (1)	0.92 (1)	1							
W5 (Energy 40%, economic 60%,)	-0.04	0.48	0.61 (3)	0.35	1						
W6 (Equal weighting)	0.86	0.89 (1)	0.88 (1)	0.96 (1,2,3)	0.22	1					
TOPSIS (Energy 16%, economic 18%, social 19%, environmental 47%)	0.77 (2)	0.69 (1,3)	0.72 (1)	0.82 (1)	0.02	0.91 (1)	1				
M1:Cap and trade	-0.25	0.29	0.45	0.16	0.96 (1,2)	0.03	-0.10	1			
M2:External cost	-0.21	0.34	0.48	0.20	0.98 (1,2)	0.07	-0.08	1.00 (1,2,3)	1		
M3:REC and external cost	-0.02	0.50	0.63	0.38	1.00 (1,2,3)	0.24	0.04	0.96 (1,2)	0.97 (1,2)	1	
M3:Joint effect	-0.06	0.46	0.60(3)	0.34	1.00(1,2,3)	0.21	0.03	0.97(1,2)	0.98(1,2)	0.99(1,2,3)	1

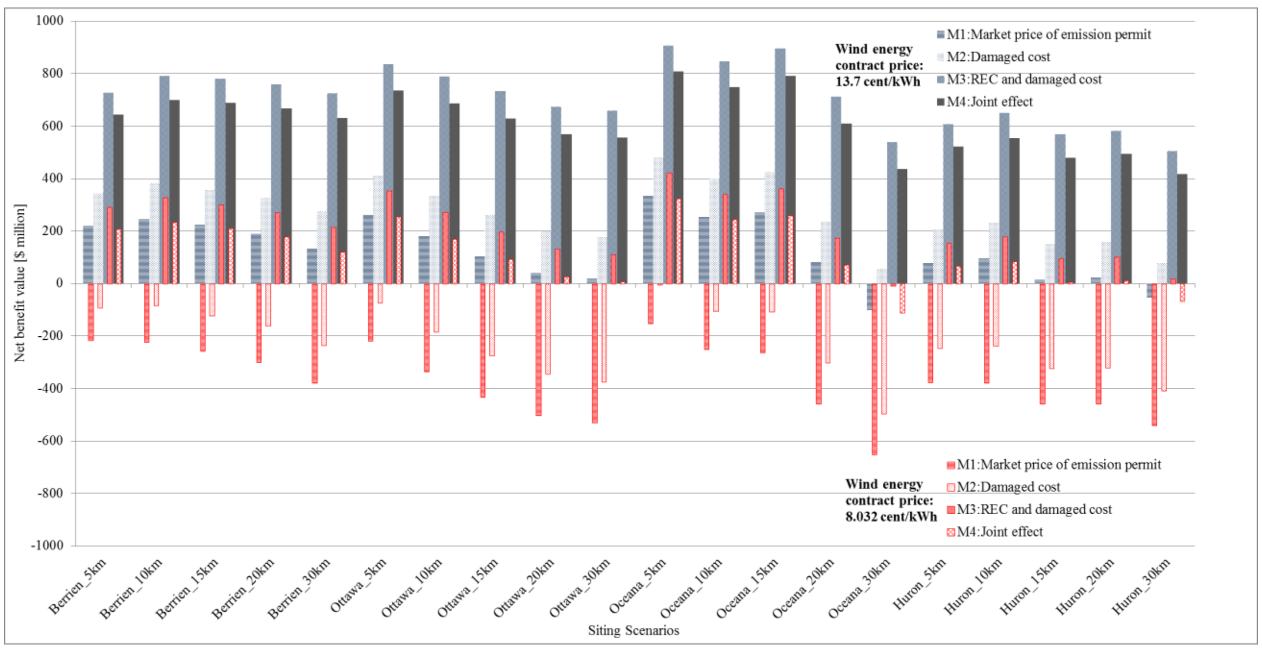


Figure 5-6 Net benefit values measured by 13.7 cent/kWh wind energy contract price (Cape Wind) and 8.032 cent/kWh (the averaged contract price of Michigan land-based wind energy projects)

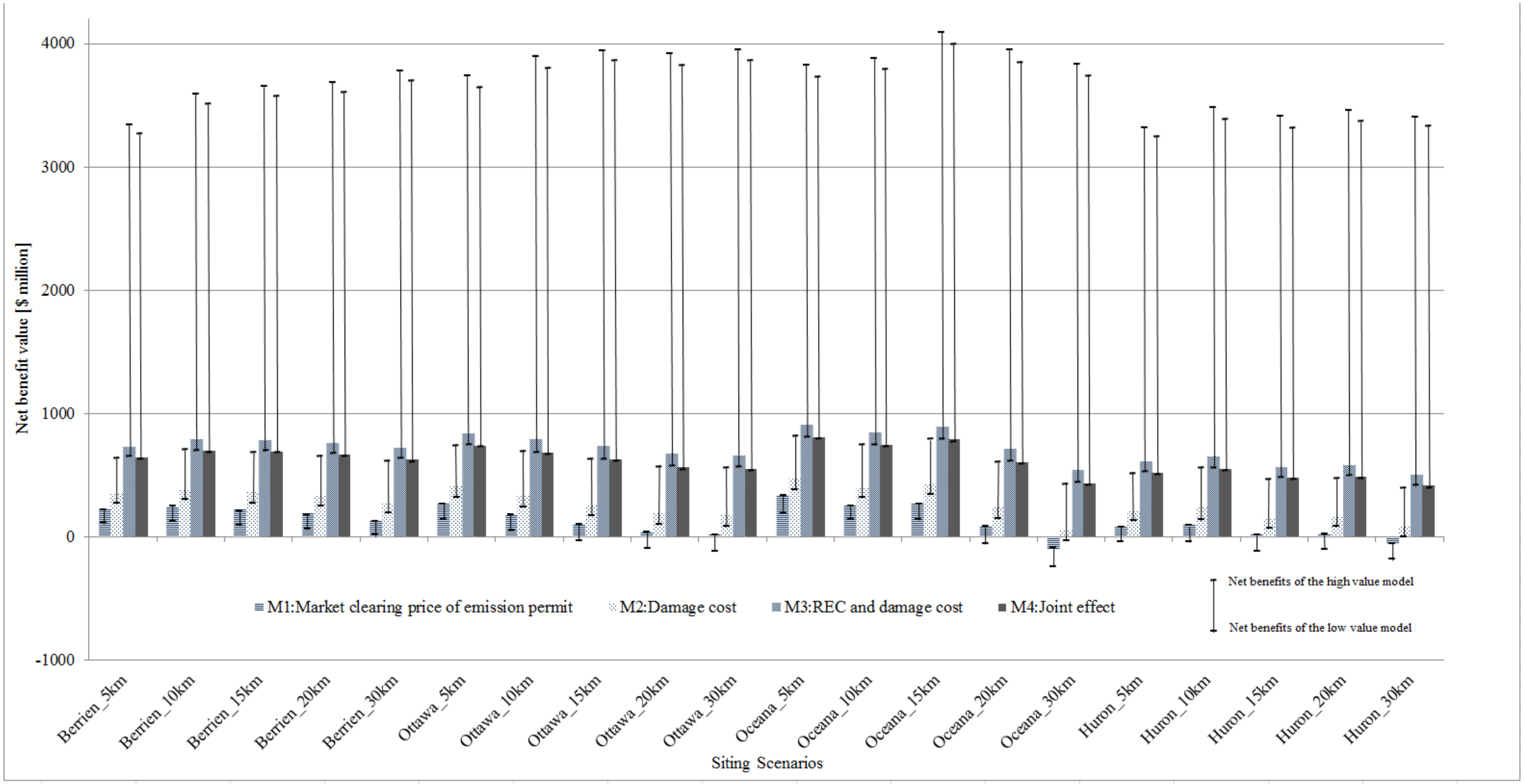


Figure 5-7 Scenario analyses of high and low environmental metric values

5-4-5. Scenario analyses of wind energy price and environmental metric values

The scenario analysis of wind energy price demonstrates that using the conservative contract price of land-based wind energy to measure the net benefit values causes the negative values for most siting alternatives (Figure 5-6). The siting alternatives can have positive net benefit values only if the environmental benefits are monetized by M3 and M4 approaches, which consider the avoided damage costs of air pollutant emissions and the gained revenue from RECs. These results suggest that (1) higher offshore wind energy contract price compared to land-based wind energy and (2) an adequate policy (REC) that considers the broad benefits of wind energy are keys to the feasibility of offshore wind energy projects.

The scenario analyses of environmental metric values demonstrate that the variation of net benefit value is less affected by the fluctuation of market clearing prices of emission permits (Figure 5-7). Instead, the net benefit values are more influenced by different estimation for the marginal damage cost of air pollutant emissions. However, both variables do not have as much impact as the REC price to the variation of net benefit values. The REC price can significantly raise the net benefit values of siting alternatives if higher price is taken into accounting.

5-5 Conclusions

The goal of this study was to examine how multiple objectives influence the OWF siting decision in the coastal areas where complex human-environment interactions require comprehensive consideration of these objectives. An MCDA method was conducted for twenty sites to evaluate criteria representing energy, economic, environmental and social objectives. Besides the criteria used to reflect financial values of OWFs, such as electricity delivered and installation costs, externality benefits and costs were assessed using different criteria, including avoided pollutant emissions, the life-cycle emission impact of wind farms, and the external cost of visual impacts. Avoided pollutant emissions were measured and monetized using approaches in terms of the market clearing price of pollutant emissions, marginal damaged costs of incremental emissions, and REC price. Finally, all objectives were weighted by subjective or objective methods to reflect different preferences and values and were aggregated and compared pairwise between the ten weighting methods.

The results show that the eleven weighting and monetization methods result in different rankings of OWF locations. Among the four measurement methods that monetize the criteria, even though the results are twice the difference or opposite in their summed dollar values, the correlation of the scenario rankings by the different monetization methods is very high. The best OWF sites according to the monetization methods were similar only to those identified by the W5 method, which weighted energy and economic objectives at 40% and 60%, respectively. However, amongst the weighting methods that included all four objectives, similar site rankings were obtained. Evaluation of sensitivity of results to alternative weighting schemes, as demonstrated here, is important for both understanding how results change with relative priorities and, where sensitivity is relatively low, reaching an agreement in siting conflicts when stakeholders have different preferences.

One contribution of this study is to apply a MCDA method in evaluating the OWF siting that is improved by including the critical externality benefits and costs of social and environmental objectives. The siting outcomes from different MCDA weighting on multiple objectives are examined with those from net benefit values measured by incorporating monetization of visual impact and avoided air pollutant emissions. This is helpful to inform the wind energy developers, policy makers, and local communities how their preferences and values on different objectives can influence the selection of OWF locations.

The criteria included in the MCDA method are for the purpose of siting evaluation. Therefore, it is not totally correct to determine the profitability of wind farm projects based on these results. Some factors may also affect the energy cost of wind farms, such as operation and maintenance, change of government policies, and variations of energy price; factors that were not comprehensively examined in this study. The monetization methods used a fixed average price value to monetize the pollution emissions. This could be another limitation and uncertainty of the study, because both the market price and the marginal avoided damaged cost are likely to change over time. If higher benefits can be received along with the market price or the marginal cost, the importance of the environmental objective will significantly outweigh the economic objective and possibly change the result of the siting scenario decision.

For future studies, the research can be extended to explore the implication of OWF siting decisions on wind-energy-related policies. Although this study has examined the influence of cap and trade, RPS, and REC on monetizing environmental externality and on the decision making of

OWF location, these policies are not specifically designed for wind farm siting. On the contrary, the wind energy resource zones (WERZ) proposed by several counties and states will expedite transmission line infrastructure construction through public policies. This requires more public investment in transmission lines as well as other supportive infrastructure, such as roads and harbors. The policy will then directly affect the siting decision made by wind energy project developers due to the saved cost. Therefore, more studies should be conducted to understand whether this is also an adequate policy for other stakeholders or the society as a whole.

Appendix F: Calculation of installation cost for the OWF siting scenario

Calculation of installation cost for the OWF siting scenario is based on the cost model developed by Dicorato et al. and validated with empirical data [101]. The total cost C_I can be expressed as follows:

$$C_I = C_{WT} + C_z + C_{CS} + C_{IS} + C_{TS} + C_{GI} + C_D$$

where C_{WT} is turbine cost, which can be expressed as follow:

$$C_{WT} = 1.4 \times 1.1 \times n_{WT} \times (2.95 \times 10^3 \times \ln(G_{WT}) - 375.72)$$

where n_{WT} is the number of wind turbines, given by 100 for 300MW OWF; G_{WT} is the rated power of each wind turbine, given by 3[MW]; The coefficient 1.4 stands for the average exchange rate of Euro to USD in 2010 (same for the following equations). The coefficient 1.1 accounts for transportation and installation additional costs.

The foundation cost C_z can be expressed as:

$$C_z = 1.5 \cdot n_{WT} \cdot c_z$$

$$c_z = 1.4 \times 320 \times G_{WT}(1 + 0.02(D - 8))(1 + 0.8 \cdot 10^{-6}(h \cdot (\frac{\phi}{2})^2 - 10^5))$$

c_z is the foundation cost for each wind turbine, [k$/turbine]; The constant 1.5 stands for the additional costs for transport and installation; D is the lake depth, [m]; h is Hub height, given by 155[m]; ϕ is rotor diameter, given by 110[m].

The collection cost C_{CS} accounts for cable manufacturing cost $C_{c,MV}$ and cable transport and installation cost $C_{i,MV}$. They can be express as follows:

$$C_{CS} = (C_{c,MV} + C_{i,MV}) \times d_{cs}$$

The assumed 33 kv submarine cables with average 240 mm^2 cable section are given by 300 [$/km] for manufacturing cost. The cable transport and installation cost is given by 648 [$/km]. d_{cs} stands for the length of cables for collection system.

The integration system cost C_{IS} mainly comes from MV/HV transformer cost C_{TR}, MV switchgear cost $C_{SG,MV}$, generation reserve cost in terms of diesel generator cost C_{DG}, and offshore substation platform cost $C_{SS,f}$. They can be expressed as:

$$C_{IS} = n_{TR} \times c_{TR} + (n_{cl} + n_{TR}) \times C_{SG,MV} + n_{HV} \times (2C_{SG,MV} + C_{BB}) + (C_{DG} + C_{SS,f})$$

where n_{TR} is the number of transformers; c_{TR} is the transformer cost; n_{cl} is the number of clusters; $C_{SG,MV}$ is the MV switchgear cost; n_{HV} is the number of HV circuits; and C_{BB} is the busbar system cost. Based on this cost model, the integration cost is given by $ 60.6 million for each siting alternative in this study.

The transmission system cost can be expressed as:

$$C_{TS} = n_{HV}(c_{m,HV} + c_{i,HV})d_{wf} + n_{HV}c_{uc,HV}d_{ps}$$

where n_{HV} is the number of high voltage lines, given by 1; $c_{m,HV}$ is unit cost of submarine HV cable, given by 938[$/km]; $c_{i,HV}$ is cable transport and installation cost, given by 1008[$/km]; d_{wf} is the average distance of the OWF from the coast, [km]; $c_{uc,HV}$ is the cost of underground land-based lines, given by 2240[k$/km]; d_{ps} is the nearest length of onshore connection to the main transmission system, [km].

The grid interface cost accounts for monitoring and general control cost C_{SE} and regulation device cost, including shunt reactor cost C_R, shunt capacitor C_C, and SVC cost C_{SVC}. They can be expressed as:

$$C_{GI} = C_{SE} + C_R + C_C + C_{SVC}$$

Based on this cost model, the integration cost is given by $ 9.8 million for each siting alternative in this study.

Project development cost C_D can be estimated as follows:

$$C_D = n_{WT} \times G_{WT} \times C_{PD}$$

where CPD is given by 65.52 [$ thousand/MW]

The installation cost estimated by this cost model for twenty siting alternatives is presented in Table F-1.

Table F-1 Installation cost of twenty siting alternatives

County	distance from shore	WT cost [$m]	Foundation cost [$m]	Collection system cost [$m]	Integration system cost [$m]	Transmission system cost [$m]	Grid interface cost [$m]	Development cost [$m]	Installation cost [$m]
Berrien	5 km	441.3	292.7	97.0	60.6	18.2	10.5	9.8	930.2
	10 km	441.3	339.9	98.2	60.6	28.0	10.5	9.8	988.3
	15 km	441.3	387.1	99.4	60.6	37.7	10.5	9.8	1046.5
	20 km	441.3	434.3	100.6	60.6	47.5	10.5	9.8	1104.7
	30 km	441.3	528.8	103.0	60.6	67.0	10.5	9.8	1221.1
Ottawa	5 km	441.3	316.3	97.0	60.6	67.5	10.5	9.8	1003.1
	10 km	441.3	481.5	101.8	60.6	77.3	10.5	9.8	1182.9
	15 km	441.3	599.6	104.2	60.6	87.0	10.5	9.8	1313.1
	20 km	441.3	670.4	106.7	60.6	96.8	10.5	9.8	1396.1
	30 km	441.3	694.0	106.7	60.6	116.3	10.5	9.8	1439.2
Oceana	5 km	441.3	316.3	97.0	60.6	18.2	10.5	9.8	953.8
	10 km	441.3	434.3	100.6	60.6	28.0	10.5	9.8	1085.2
	15 km	441.3	481.5	101.8	60.6	37.7	10.5	9.8	1143.4
	20 km	441.3	670.4	106.7	60.6	47.5	10.5	9.8	1346.8
	30 km	441.3	859.2	111.5	60.6	67.0	10.5	9.8	1560.0
Huron	5 km	441.3	269.1	95.7	60.6	235.5	10.5	9.8	1122.6
	10 km	441.3	292.7	97.0	60.6	245.3	10.5	9.8	1157.2
	15 km	441.3	363.5	98.2	60.6	255.0	10.5	9.8	1239.0
	20 km	441.3	363.5	98.2	60.6	264.8	10.5	9.8	1248.7
	30 km	441.3	434.3	100.6	60.6	284.3	10.5	9.8	1341.5

Chapter 6 Conclusions

6-1 Research findings and contributions

6-1-1. Improving the accuracy of wind energy potential estimation

Wind speed profiles are the keys to predicting wind-energy generation and necessary for determining how offshore wind farm locations meet energy goals. Wind speed data can be collected from weather stations or anemometer masts, but this direct collection of these data is constrained by finances, data duration, location, and height accessibility. Two mathematical models, the power law and the Weibull distribution, are commonly used to accurately represent wind characteristics. The former is used to extrapolate wind speed at higher elevations from lower elevations by considering vertical wind speed gradients due to the effect of wind shear. The latter is a representative of frequencies at different wind speeds (hourly wind speeds) over a certain time period (one year).

In Chapter 2, I developed a regression model and a geostatistical model to estimate wind speed profiles at sites for which there are no measurements, by utilizing existing wind speed data. The results demonstrate that using the regression model to determine the Hellman exponent of the power law results in greater accuracy of wind speed estimation than applying the exponent of 0.14 to the power law. Following this vertical extrapolation of wind speed, the shape parameter for an approximate Weibull distribution at each weather station location is extrapolated to remote sites through an ordinary Kriging model. The result of this horizontal extrapolation shows that a suitable choice of the shape parameter can reduce the variation of wind energy output estimation error compared to the standard approach of selecting the value of 2 as the shape parameter for the Weibull distribution.

6-1-2. Illustrating environmental benefits and impacts of offshore wind farms

One benefit of electricity generated from wind energy is its potential to improve environmental quality. The research utilizes a process-based LCA to understand environmental impacts during the lifespan of an offshore wind farm. The environmental burdens per functional unit (the delivery of one kWh of wind generated electricity) varies based on county location and distance from shore, due to variation in the wind energy resources and required modifications of wind farm systems. The general recommendation for siting OWFs is to install them closer to the coast to minimize environmental impacts. However, the environmental performance of any siting scenario is very sensitive to the foundation type utilized. Generally, in transition zones where multiple foundation types are economically feasible for wind projects, the monopile foundation outperforms the gravity-based foundation, and the tripod foundation outperforms the floating foundation with respect to cumulative energy demand (CED), global warming potential (GWP) and acidification potential (AP) metrics. The GWP values of the twenty scenarios examined in this research are relatively higher than previous wind farm LCAs. This variation may be attributed to differences in wind energy potential, the wake effect, and the transmission losses. Moreover, the burdens from wind turbine foundation manufacturing and installation will consume more energy and materials for offshore wind farms, relative to land-based wind farms. Finally, the distance to transport wind farm components is a crucial factor in influencing its environmental performance. This is especially obvious for wind farm scenarios with gravity based foundations, which are massive and thus require high petroleum consumption for transport.

The environmental benefits of wind energy compared to the life-cycle impact were analyzed in Chapter 5 through measuring the reduced or displaced air emissions of burning fossil fuels. Due to the intermittent nature of wind energy, emissions are expected to be reduced or displaced mainly for non-baseload electricity generation power plants, including coal, petroleum and natural gas power plants. After the quantifying the reduction in emissions, four methods are introduced to evaluate and monetize the environmental benefits: 1) a market clearing price for a pollution allowance permit, 2) a marginal damaged social cost of an incremental increase in pollution emissions, 3) a market price of renewable energy certificates (REC) due to the RPS regulations, and 4) joint effect of pollution and renewable energy regulations on environmental benefits. According to our study, the REC approach leads to higher monetized environmental values of OWFs.

6-1-3. Characterization and valuation of visual impacts of offshore wind farms

The development of OWFs has faced objections from local communities. One of the common disputes arises from the visual interference of wind turbines. To better inform the stakeholders about the visual impact, we built a model using GIS to calculate the number of residents and the coastal areas that will be visually impacted by the installation of the OWFs. The results are then further transformed into a dollar value by using the external cost of visual impact calculated from WTP data for moving wind turbines farther offshore. Although the absolute value of the monetized cost associated with visual impacts is relatively small compared to the installation cost or the revenue earned from total energy generation, a scenario analysis demonstrates that the external cost of visual impacts may have significant influence on determining OWF location in densely populated visually impacted coastal areas or in areas where concerns about the visual quality are higher than average (i.e. have a willingness to pay more for moving wind turbines farther offshore).

6-1-4. An integrated assessment to inform stakeholders the trade-offs among objectives

Because OWFs are one type of land/water use in coastal areas, they face competition from other existing and potential activities in these limited spaces. The competition can be concretely reflected in terms of objectives concerned for installing OWFs. I therefore conducted a multiple-objective analysis of OWF siting in order to understand the influence of preferences and values for the objectives of energy production, economic performance, environment impact and benefit, and societal acceptance on determining OWF locations. Three groups of MCDA weighting methods were compared for evaluating the optimal wind farm location, including subjective weighting, objective weighting and monetization methods.

By comparing the rankings of siting scenarios using different weighting methods, a significant disparity was found between monetization methods and both subjective and objective weighting. The monetization methods can be treated as a preference only weight on energy and economic objectives. Therefore, they have similar ranking results only with one particular subjective weighting method, which weights energy and economic goals at 40% and 60%, respectively. Another important finding of the multiple objective assessments is that different preferences and values for goals can be resolved with a representative weighting method.. The ranking of the siting scenarios based on this representative method has the highest similarity to the rest of weighting methods.

The methodologies developed and the results presented in this research provide guidance for the selection of OWF locations, OWF technology improvement, the resolution of visual impact disputes, and the design of the wind energy resource zone policy. These factors should be carefully assessed because they can collectively determine the success of an OWF project. Results from this study are expected to be helpful to the various stakeholders involved in OWF deployment, such as wind farm developers, wind-farm construction companies, local communities, and public policy makers.

6-2 Limitations and constraints

Several limitations and constraints related to data, methodology and application are important to highlight. The first type of limitation is the lack of sufficient data. For example, the extrapolation of wind speed from lower to higher elevation by the power law and the predicted Hellman exponent through the regression model requires more validation by collecting simultaneously measured wind speeds at different heights for more locations and over longer time periods. Understanding the wind characteristics from existing measured data is helpful for OWF planning. The measurement of wind speed by anemometer towers above the waters can increase the certainty of Kriging prediction of the shape parameter in the Weibull distribution. The prediction models for the Hellman exponent and the shape parameter both suffer from the lack of suitable wind data. I confronted another data issue in the LCA study of OWF siting. The data quality and availability may influence the interpretation of the LCA results. Since OWFs are still in the planning or construction stages in the U.S., none of them can yet provide empirical data during the operation, maintenance, and decommissioning stages. This lack of data availability might diminish accuracy of OWF environmental performance results. Additionally, the logistics for component manufacturing is undefined due to the inaccessibility of the proprietary data. This could lead to influencethe life cycle environmental impact results of OWFs. Finally, the results are dependent of the research scope selected. If the OWF LCA scope were to include assessing the environmental impact of supportive infrastructure and equipment; such as harbors, ships, and cranes; then the LCA would need to account for the impacts associated with the induced demand from shipbuilding plants.

The methods used in this study have limitations for explaining the environmental impacts and benefits at different spatial scales. This is particularly important in the environmental impacts measured by the LCA and the environmental benefits calculated by the displaced pollutants of non-baseload electricity. The methods, which both use global data to evaluate the environmental impacts and benefits, may not be able to reflect their variation at the local level. For example, the life cycle inventory of an OWF was collected based on the average of American or European activities/processes/materials, ignoring that a certain level of local variation exists. A similar phenomenon occurred when the displaced pollution of wind energy is measured by the emissions from non-baseload electricity of the averaged power plants in Michigan. The real replacement from matching the energy supply and demand in the dynamic price market is not well represented. Therefore, this study fails to specify the emission reductions in particular high pollution power plants, from which the neighboring communities could gain greater environmental benefits.

Another limitation of the methods in this study is the inability to describe the change of stakeholders' attitudes toward OWFs through time. In the evaluation of OWF visual impact, the WTP for moving wind turbines farther based on *ex ante* OWF installation may change as the residents realize the real impact *ex post* the OWF installation. The dynamic change of preferences and values is also expected to occur in the *ex ante* selection of weighting on various objectives of OWF. The limitation coincidently reflects the current reality that there are no operational OWFs in the U.S. The result of this study should be carefully compared with OWF studies in the Europe, where people have had more experience with OWFs.

Those who want to extend the finding in this study have to acknowledge the application constraints rooted in some key assumptions. First, the studied OWF scenario is assumed to be composed of 100 x 3MW Vestas wind turbines, but the technical specification of wind turbines changes so rapidly along with wind industry development that energy generation efficiency, materials and energy consumption, and the size and height of wind turbines may be very different for each wind farm project. Next, the visual impact analysis only looks into residents' attitudes toward visual impacts of wind turbines. The study does not consider the attitudes of short-term visitors, such as tourists. Their attitude may also influence the success of wind turbine installation in those places that significantly rely on the economic activities related to tourism. Finally, the decision of OWF siting is very site-specific. Any generalization of this study in order to apply it elsewhere must distinguish the possible disparities caused by wind energy resources, terrains, supportive infrastructure, water bathymetry, and community composition. Even some high level factors, such as renewable energy policies and the existing composition of electricity supply, can differ from region to region. These can influence the choice of the optimal OWF location when multiple objectives are taken into account.

6-3 Future research

The intermittent characteristic of wind is a concern that impedes the widespread application of electricity generated by wind. Several methods are proposed to cope with this issue including storage, backup power plants, demand side management, integration with a larger power grid, and wind farm siting. Using wind farm siting as a strategy can have multiple potential benefits. First, with an increasing number of wind farms installed, the fluctuation of wind energy can be reduced. Secondly, if wind speed patterns are coincident with the electricity demand of the load center, they can then serve as a peak load supply. The former benefit is reduced by one wind energy resource zone policy reduces the investment of transmission lines, but increases the risk of instability in the power grid. The trade-offs between stable wind energy generation and the reduced infrastructure investment must be further investigated. Besides the baseload potential of wind energy in terms of distributed generation, the non-baseload potential of wind energy requires wind energy generation at locations where the maximum generation meets the peak demand for different time scales. Better selection of wind farm locations with this aim can also reduce the reserved capacity of power plants.

The study of OWF LCA demonstrates that foundation types can be a crucial component in determining the environmental impact of siting scenarios. Attention should be paid to major impacts caused by different contributing factors associated with foundation types including manufacturing location, transport distance, and decommissioning strategies. A study using practical data for a sensitivity analysis could reduce the global data problem by reflecting local variation. Such a study could also help clarify the influence of transport logistics on environmental impact. Moreover, the recycling processes at the end of life is particularly important for wind farms because they are mainly composed of steel, which can be recycled with a high recovery percentage. The way that steel is produced and the percentage of steel that is recycled will collectively determine the energy and material consumption and further environmental performance.

The visual impact of wind turbines is affected by the combination of weather; contrast between turbines and landscapes; stakeholders' preferences and values; and many physical factors such as the size, color, distance, number, and arrangement of wind turbines. The simplified viewshed evaluation model built in this study can be further developed to reflect the factors influencing the social acceptance of OWFs. Among these factors, the arrangements of wind turbines might be the most interesting because it will simultaneously influence the energy generation due to the wake effect, the change in electricity loss from different lengths of collection lines, and the extent of the visually impacted areas. Therefore, any design of wind turbine arrangement will become a multiple criteria decision.

Another research issue that can be addressed is developing a deeper understanding about stakeholder attitudes toward the visual impact of wind turbines. This research has already shown how the *ex ante* OWF siting is influenced by preferences and values on multiple objectives. A research gap that can be fulfilled is to conduct an interactive MCDA through different life cycle stages of OWFs. To explore the knowledge of decision making on renewable energy sources in that research, more policy issues related to the wind energy development can be added, especially compensation for wind turbine impacts, setback distance between wind turbines and communities, and revenue return of wind generated electricity. OWF siting is not a static decision, but rather a dynamic process in which the people involved will be influenced by the media, social interactions, and changing personal knowledge and preferences. Meanwhile, stakeholders have the potential to modify the existing framework of social, economic or political conditions by changing or designing policies that are beneficial for them. Through such research, global renewable energy policies with regard to RPS and WERZs can be improved by articulating local concerns and can gain more support from communities and interested groups.

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