Using Geographic Information Systems to Analyze Suitable Locations for Water Wind Turbine Farms in Lake Michigan

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Abstract

The new frontier for renewable energy is wind turbines on water bodies. Determining the best site location is vital in terms of productivity and cost-effectiveness. This research study analyzed geographic data available for water wind turbines utilizing Geographic Information Systems (GIS) to determine optimal sites for water wind turbine farms in Lake Michigan. Data included in the analysis were water depth, annual wind speed, distance to shoreline, shipping routes and proximity to urban population centers. The efficiency of water wind farms is most dependent upon three factors: water depth, wind speed and distance to shoreline for access to power grids. Water depth data was classified into three classes using equal intervals. A three point rating scale was developed to categorize wind speed. Distance to shoreline was determined using GIS. While water depth, wind speed and distance to shoreline were the principal factors considered for site location, various other elements needed to be taken into consideration as well. Two viable locations were identified as suitable locations for a water wind farm.

Introduction

Today, much of our electrical energy comes from non-renewable, polluting sources such as oil, petroleum and coal. The quest for alternative energy sources throughout the globe has heightened as the cost of oil has risen and the need to reduce greenhouse gas emissions continues to grow. A November 12, 2008 report by the International Energy Agency (IEA) states "if demand (for oil) remained flat, by 2030 the world would need to find new oil production equivalent to four Saudi Arabias, merely to offset oil field decline" (Gies, 2008). According to the American Wind Energy Association (2009), the generation of electricity is "the largest industrial source of air pollution in the U.S."

Wind energy is clean, renewable, cost effective and its use to create energy reduces greenhouse gas emissions. The capacity of wind to generate energy worldwide is estimated to be 94,112 megawatts (MW) and "for every megawatt of wind energy produced, $1 million in economic development is generated" (American Wind Energy Association, 2009). It is estimated that in the U.S. alone, wind energy could produce more than two times the electricity currently produced today (American Wind Energy Association). While numerous wind turbine farms have sprung up over land, wind power over water has the potential to generate

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even more energy. Nonetheless, water wind energy is not a new concept. For example, Europe has been using offshore wind technology since 1991 (American Wind Energy Association). In 2001, SWAY, a wind energy technology company in Norway built a water wind turbine over the North Sea. It is the world's largest water wind farm (SWAY, 2010).

Considerable research has been conducted documenting the reasons for the advancement towards offshore wind farms and Lake Michigan has been viewed as a great wind resource (United States Department of Energy, 2010). Steve Smiley, an Energy Economist, has been studying wind energy in Lake Michigan. Smiley points out "offshore windmills can generate up to five megawatts, about three times what an on-shore windmill will deliver" (Hinter, 2008). Walt Musial, an engineer for the United States Department of Energy, has also been studying the potential for a water wind turbine over Lake Michigan and believes wind energy produced from offshore technology is approximately two times greater than onshore (Richmond, 2006-2009).

The fact Lake Michigan is considered a hot spot for wind power and that there is a need for alternative energy sources in Wisconsin has led to an energy independence movement. A report by the Public Service Commission of Wisconsin states Wisconsin has "few native energy resources, with the exception of renewable sources such as wind, hydroelectric, solar, and biofuels" (Public Service Commission of Wisconsin, 2009). The report also states by 2015 about 10 percent of electricity in Wisconsin will need to come from renewable sources (Public Service Commission of Wisconsin).

More feasibility studies are inherently needed to harness the nation's wind resources efficiently. A Geographic Information System (GIS) can be used to analyze the viability for a water wind farm at a given location. With GIS, data such as average wind speed, water depth and distance to shoreline can be integrated into one analysis. The purpose of this project was to determine the most suitable location for a water wind farm on the west shoreline, or the Wisconsin side of Lake Michigan. While several recent studies have been conducted to establish a wind farm near the east shoreline, bordering the state of Michigan, this current project focused on areas closer to Wisconsin.

Methods

Data Obtained

The data for this project consisted of five layers: water depths for Lake Michigan, wind speeds over Lake Michigan, Lake Michigan shoreline, shipping routes across Lake Michigan and proximity to major urban areas of Wisconsin. Data on power grids were also used for this analysis because wind turbines must be connected to a power grid. Data were obtained through several internet sources including research studies and supplementary reports.

Water Depths

Lake Michigan water depths were bathymetric files obtained from the Great Lakes Information Network website (Great Lakes Information Network, 2008). Water depth information was contained in a shapefile with a geographic coordinate system of World Geodetic System (WGS) 1984. This shapefile was transformed to North American Datum (NAD) 1983, consistent with the shoreline shapefile.

Figure 1 shows the water depth for Lake Michigan.

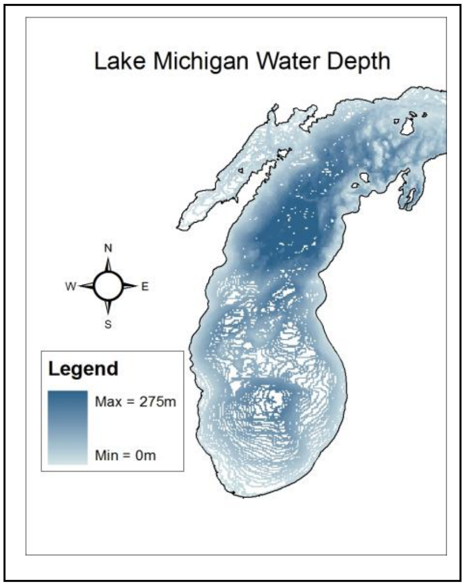

Figure 1. Water depths for Lake Michigan, converted to a Geographic Coordinate System (GCS) with a NAD 1983 Datum.

Finally, the raster was reclassified. Water depths were classified into three classes using the equal interval method (Table 1).

Table 1. Reclassified water depth values.

Old Value	**New Value**
0 to 91.666 meters deep	3
91.666 to 183.333 meters deep	2
183.333 to 275 meters deep	1

Equal intervals were used for two reasons. First, the equal interval method divided the data evenly between each category. For example, the first category ranged from 0 to 91.666 meters in depth and was assigned a value of 3 representing suitable depths for a water wind farm. The second category, assigned values of 2, ranged from 91.666 meters to 183.33 meters deep. The third category ranged from 183.333 to 275 meters deep and was assigned a value of one, which represented a poor location for a water wind farm.

Another reason for using equal intervals was because the water depth data is linear. For example, there are few outliers in the data. Trenches in the lake floor bed would explain any outliers. Any gaps in the data would offset a category for water depths. Suppose there was only one location with a measurement in the second category (91.666 to 183.333 meters). With equal intervals, each depth category had relatively the same number of features for the map.

Shallow waters are most suitable for a water wind farm for several reasons. First, construction costs are minimized due to the type of construction method used for the turbines. Four different types of foundations can be used to anchor turbines into the lake bed in shallow water (Public Service Commission of Wisconsin, 2009). These include a concrete gravity base, steel, thin-walled cylindrical shell with ring footing and suction caisson (Public Service Commission of Wisconsin). The concrete gravity foundation is the most popular but the size and weight is a disadvantage (Public Service Commission of Wisconsin). Secondly, wind turbines located in shallower waters are easier and more cost effective to maintain (Public Service Commission of Wisconsin). Therefore, the first category, from 0 to 91.6 meters deep, was given a new value of three representing the most suitable area for a water wind farm. The next category from 91.6 meters to 183 meters in depth was given a value of two because it is second most suitable for a water wind farm area. Finally, the last depth category, from 183.333 to 275 meters deep, was assigned a value of one identifying this area as the least suitable for a water wind farm.

Wind Speeds

Average annual wind speeds for Lake Michigan were obtained from the United States Department of Energy National Renewable Energy Laboratory (United States Department of Energy, 2010). However shapefiles were not found directly for wind speeds over Lake Michigan. A TIFF image was located showing average wind speeds for the entire United States. The TIFF image was then geo-referenced to the Lake Michigan shoreline layer, which had Geographic Coordinates. Figure 2 illustrates average wind speeds over Lake Michigan.

A polygon shapefile was created with the same spatial reference as the shoreline shapefile. Wind speeds were digitized over Lake Michigan using the on-screen digitizing method.

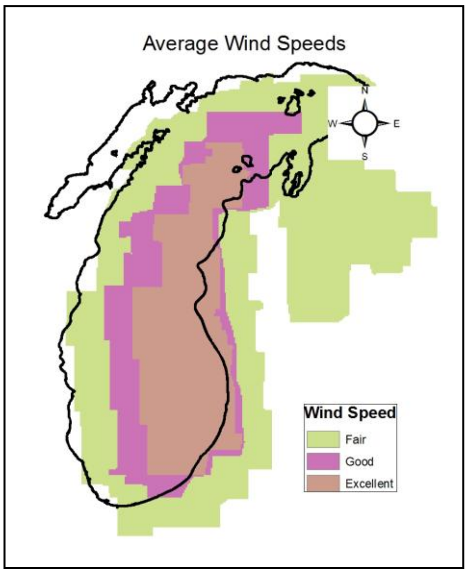

Figure 2. Average wind speeds over Lake Michigan.

A new field was created in the attribute table. Each polygon corresponded to a particular wind speed rating, from three to five, with five representing the strongest winds. A value of three represented “fair” wind speeds, whiles a value of four represented “good” wind speeds. Table 2 illustrates the wind speed ratings derived from the original TIFF image.

The TIFF map had seven ratings. The highest ratings, six and seven, were found in Alaska. However, wind speeds in Lake Michigan contained three values (see Table 2).

Table 2. Categories of wind speed ratings from the United States Department of Energy.

Category	Wind Speed Rating	Speed (meters per second)	Speed (miles per hour)
3	Fair	6.4 – 7.0	14.3 – 15.7
4	Good	7.0 – 7.5	15.7 – 16.8
5	Excellent	7.5 – 8.0	16.8 – 17.9

Raster Calculator for Wind Speeds and Water Depths

Wind speeds and water depth were the most important layers in this analysis. Therefore they were added together to find the first-case “suitable” areas for a wind farm area in Lake Michigan.

The wind speeds, water depths, and distance to shoreline layers were all added together.

Distance to Shoreline

A shapefile showing the shoreline of Lake Michigan was also obtained from Great Lakes Information Network (2008). The shapefile consisted of polylines. This shapefile had a Geographic Coordinate System (GCS) spatial reference in NAD 1983.

This image was misleading and required a re-classification. The Public Service Commission of Wisconsin (2009) suggests it is more cost effective to have water wind turbines located as close to the shoreline as possible. Therefore distances near the shoreline (less than 20 miles) were re-classified with a value of ten. A value of ten represents a suitable location for a water wind farm. Distances farthest from the shore, those greater than 20 miles from shoreline, were given a value of one (Figure 3).

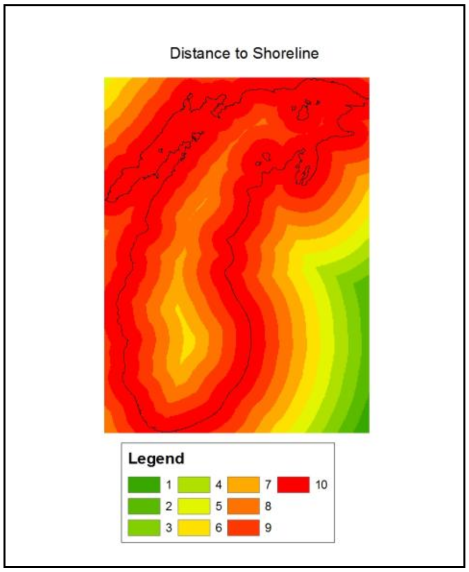

Figure 3. Distances to shoreline. The values of 10 represent areas closest to the shoreline and hence are the most suitable for a wind farm.

The distance raster was added to the wind speed and water depth rasters. The following three mask grids were created as a result from the raster:

1. A mask grid was created to find all values less than 15.
2. A mask grid was used to find all values of 15 or 16 from the raster. The values of 15 and 16 were both selected because they were a starting value based on wind speeds, depth, and distance from shore. All features were converted to points as a medium suitability analysis for the map.
3. All values greater than 16 were selected and saved as "Highsuit." These represent areas of high suitability based on distance, wind speeds, and water depths. The majority of these areas were congregated towards the state of Michigan. A previous study done by the Public Service Commission of Wisconsin already identified areas on the Michigan side of Lake Michigan. This study only focused on identifying viable areas on the west shoreline or the Wisconsin side of the lake. Therefore areas with the highest suitability from the calculated result were not mapped for this project.

For each of the above, each raster was converted to point-features. This was done to show the exact locations of water wind turbines and how close they are to one another.

Shipping Routes

Shipping routes were obtained from the Great Lakes Information Network website. This shapefile had a spatial reference of NAD 1983 which was consistent with the shoreline shapefile (Figure 4). The final suitability point shapefiles were mapped using the Spatial Analyst. A query was used to find all "suitability points" that were within 1.5 miles of shipping lanes. All points within a distance of 1.5 miles from the shipping routes were selected. A distance of 1.5 miles was used as a minimum distance because of results provided by previous wind research studies conducted near Cape Cod, Massachusetts. According to the

Massachusetts Fishermen's Partnership (2006), for a wind farm located off the coast of Cape Cod, wind turbines should be located at least 1.5 miles from the shipping lanes. Consequently, a 1.5 mile distance between the wind turbine blades and the shipping lanes was used. All points within 1.5 miles from the shipping areas were considered too close to the shipping routes.

Areas for a wind farm were further deemed as "pockets." These areas were chosen based on shipping routes and distances between blades. One such area lies near Milwaukee.

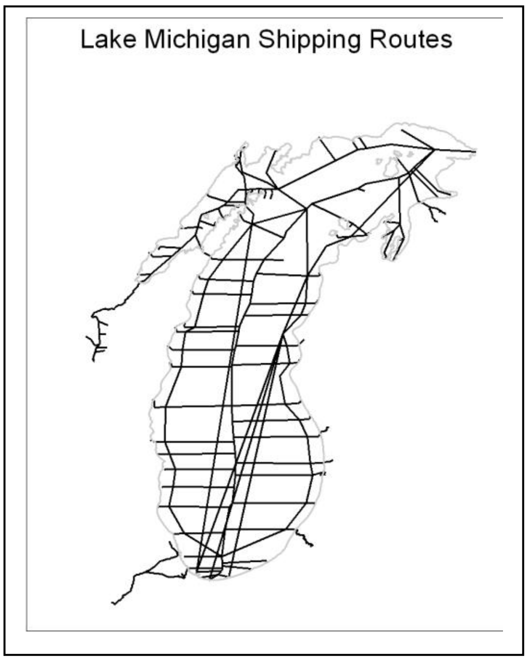

Figure 4. Shipping lanes in Lake Michigan.

Urban Areas

Population areas are an important factor to include in a water wind farm location feasibility study because with larger, denser population centers there is greater potential to serve more customers cost-effectively with wind energy and connect to a power grid. Therefore proximity to urban population centers was another key factor considered for this project.

Population data for the major population centers in eastern Wisconsin was obtained from the United States Census Bureau. The population data was analyzed and mapped (United States Census Bureau, 2000). An urban areas shapefile was obtained from the Great Lakes Information Network website. Each urban area consisted of a polygon. This shapefile also had a coordinate system of NAD 1983.

Another matter taken into consideration was that energy produced from a wind farm in Lake Michigan may not necessarily be used in the Mid-West area. Energy companies often transport the electricity to various locations throughout the United States provided there is adequate transmission capacity. Data obtained from the United Stated Department of Energy identified major power distribution centers in Eastern Wisconsin (United States Department of Energy, 2010).

Factors Not Considered

Ice cover is another factor that could be considered when determining site location for a water wind turbine farm on Lake Michigan (Public Service Commission of Wisconsin, 2009). However it was not included as an attribute investigated or mapped in this study.

The lake bed is also important for this analysis. Lake bed type determines which type of construction method to use for the turbines. Data on lake bed was not found for this project.

Finally wave action is another factor that could be considered (Public Service Commission of Wisconsin, 2009). Wave action is important because the types of construction patterns depend on wave action. However wave action was not evaluated in this particular study for Lake Michigan as data were unavailable for wave motion on Lake Michigan.

Environmental Data

Environmental data could also be considered for site location of water wind turbines in Lake Michigan (American Wind Energy Association, 2009). Such data includes bird migratory patterns and fishing habitats.

Qualitative data such as fishing areas or bird migration patterns would require a significant amount of in-depth research and therefore, this type of qualitative data was not included in this particular project. Additionally, effects on fishing populations are still unclear (American Wind Energy Association, 2009).

Results

Water Depths and Wind Speeds

Locations measuring the highest wind speeds tend to be located in the middle of the lake. These areas were not considered for the following reasons. First, according to the Public Service Commission report, areas closest to the shoreline would be more suitable for an anchored wind turbine. Secondly, wind farms located far from shore are more costly overall (Public Service Commission of Wisconsin, 2009).

Distances to Shoreline

Areas of low suitability tended to be located more than 20 miles from the shoreline. Distances too far were not feasible because once again, the farther from shore, the higher the construction, maintenance and repair cost for the turbines.

Areas of medium suitability, used for this project, were located less than 20 miles from shoreline. For example, a distance of 20 miles or less was considered more feasible because of the construction, maintenance and repair factors (Public Service Commission of Wisconsin, 2009). Additionally, according to the Public Service Commission, the farther offshore the wind farm, the greater the distance the electricity will have to be moved to the reach shore (Public Service Commission of Wisconsin). The farther electricity has to travel the less efficient the generation becomes (Public Service Commission of Wisconsin).

Shipping Routes

Shipping routes tended to crisscross the southern portion of Lake Michigan and are less concentrated in the middle of the lake. Two main shipping lanes run north-south, splitting the lake in half. There are large areas of open water between each shipping route and especially toward the Wisconsin shoreline. These areas were suitable for water wind farms.

Proximity to Urban Areas

Both of the medium suitability locations were located near urban areas. One was located near Milwaukee, Wisconsin. Milwaukee had a population of roughly 953,000 people in 2000 according to the US Census Bureau (United States Census Bureau, 2000).

Green Bay was the other location for a possible water wind farm. Green Bay had a population of 102,300 people in the 2000 Census (United States Census Bureau, 2000).

Low Suitability

An area of low suitability was found just east of Manitowoc, Wisconsin. This area was recognized as a possible location for several reasons. First, this area has average annual wind speeds between 14.0 and 16.8 miles per hour (United States Department of Energy, 2010; National Renewable Energy Laboratory, 2010). Second, this area has relatively shallow waters. Nonetheless, this area was low suitability because it was more than 20 miles from shoreline.

This area measured 10 miles across from east to west by 20 miles from north to south at its widest point.

Medium Suitability

The analysis showed two areas deemed as medium suitability for a water wind turbine farm in Lake Michigan. One area is located east of Milwaukee, Wisconsin (Figure 5) and the other area is found along Wisconsin's Green Bay peninsula (Figure 6).

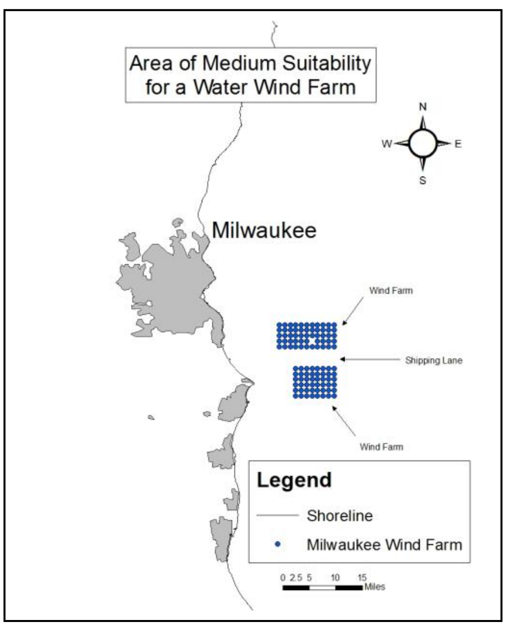

Figure 5. Area of medium suitability for a water wind farm near Milwaukee, Wisconsin.

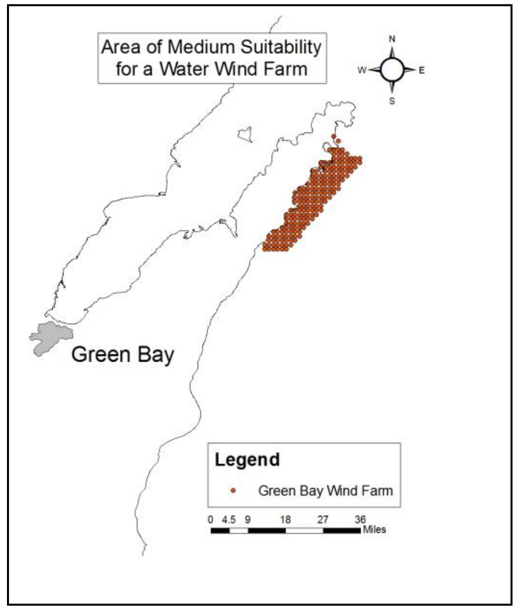

Figure 6. Area of medium suitability for a water wind farm near Green Bay, Wisconsin.

The Milwaukee area measured 10 miles from east to west, by 14 miles from north to south at its widest point. The wind farm site near Green Bay measured approximately 16 miles east to west at its widest point and approximately 22 miles north to south at its widest point. The two recognized areas were labeled as "Medium 1" for Milwaukee and "Medium 2," for the area near Green Bay. Both areas were chosen for several interrelated reasons.

Proximity to the shoreline was one main factor, making construction and maintenance easier and more cost effective (Public Service Commission of Wisconsin, 2009). Wind speed was also a factor.

While wind speeds farther out on the lake were higher, wind speeds in the medium suitability areas were strong and stable enough to generate abundant electrical power. Another reason these two locations were identified for medium suitability was because of the shallow waters. With shallow waters the anchors and cables do not need to extend too far to reach the lake bottom (Public Service

Commission of Wisconsin, 2009). One possible impediment to the Milwaukee site is the shipping lane through the center. However there is a 1.5 mile distance between turbine blade and shipping lane.

Table 3 shows the results for each location for low and medium suitable areas based on average wind speed, water depth, distance to shoreline, and proximity to urban areas.

Table 3. Summary of the findings for the feasible site locations based on wind speed, water depth, distance to shoreline and proximity to urban area.

Type	**Location**	**Wind Speed**		**Water Depth**	
		Med.	High	Shall	Deep
LS	1	X		X	
MS	2	X		X	
MS	3	X		X	
Type	**Location**	**Distance to Shore**		**Distance to Urban Area**	
		<20	>20	<75	>75
LS	1		X		X
MS	2	X		X	
MS	3	X		X	

Type: LS = Low Suitability
MS = Medium Suitability
Location: 1 = Manitowoc and Sheboygan, WI
2 = Milwaukee, WI
3 = Green Bay, WI
Note: Distance is measured in miles

Discussion

Lake Michigan has been viewed as a hot spot for a water wind farm. The analysis from this particular project identified two viable locations for a water wind farm. One location lies just east of Milwaukee, Wisconsin and the second area lies east of Green Bay. Both are medium suitability based on average annual wind speed, water depth, distance to shoreline, shipping routes and proximity to urban areas.

Power Capacities for Milwaukee and Green Bay

Each turbine in a water wind farm can produce up to five megawatts of electrical energy (American Wind Energy Association, 2009). For this analysis, assume that electricity produced from the wind turbines will be utilized in the region.

One five-megawatt blade can generate enough electricity to power about 1,400 households (American Wind Energy Association, 2009). Milwaukee, Wisconsin has approximately 377,730 households according to the 2000 census (United States Census Bureau, 2000). Therefore, the Milwaukee area would require 270 turbines for the water wind farm to generate power for all households. However, this study concluded that the Milwaukee site could only accommodate 140 turbines without interfering with shipping routes. The wind farm near Milwaukee meets all requirements except for the power generation capacity. Green Bay, Wisconsin has approximately 41,600 households according to the 2000 census requiring 30 turbines (United States Census Bureau, 2000). The Green Bay site can definitely accommodate 30 turbines without interfering with shipping lanes. The Green Bay site meets all the requirements including the power generation capacity (Table 4).

Based on Cape Wind (2010), studies for a water wind farm near Cape Cod, Massachusetts, blades were placed at a distance of 0.54 nautical miles or about 0.621 statute miles apart (Cape Wind, 2010). The distances from Cape Cod were used as a minimum distance between turbines in Lake Michigan. Table 5 illustrates the proposed spacing pattern for turbines to be utilized at each identified wind farm site.

Table 4. Number of offshore turbines required to generate electricity for the number of households designated at medium suitability locations.

Location	**Number of House-holds**	**Recom-mended Number of Turbines**	**Number Of Turbines Proposed**
Mil-waukee	377,730	270	140
Green Bay	41,600	30	30

Table 5. Recommended spacing pattern for offshore turbines.

Site Location	Miles between each turbine -- East to West	Miles between each turbine- North to South
Milwaukee	0.64	1.0
Green Bay	0.64	1.0

Sources of Error

One restriction with the data dealt with the wind speed layer. When digitizing, the shoreline could not be lined up exactly with the source map showing wind speeds. The error is evident in the southern-most area of Lake Michigan towards Chicago, Illinois. This problem affected the accuracy for wind speeds over Lake Michigan. For example, the boundary between the "Good" and "Excellent" wind categories could be slightly inaccurate for the purpose and mapping analysis.

An additional limitation encountered during this project was the water depth layer. Data were incomplete for the lakebed. Some areas were not mapped because it is not feasible to sample the entire lakebed. More depth measurements need to be performed.

Connecting wind power to electrical power grids or substations can be seen as another possible limitation. There appears to be a definite need to develop additional transmission capacity throughout the United States. According to Modernize the Grid (2010), "there is currently almost 300,000 MW of wind projects, more than 20% of our electricity needs, waiting to connect to the grid because there is inadequate capacity to carry the electricity they would produce." However, while there appears a necessity to improve current transmission to accommodate power generated by wind, upgrading transmission is not considered the main expense in the development of future renewable energy. Transmission costs are only 8% of the total price of transmission and the actual generation of the energy is about 66% of the cost, while actual distribution of the energy is 26% of the total cost (Modernize the Grid, 2010).

According to the American Wind Energy Association, other drawbacks to the development of wind turbines over water that need to be considered are multifold:

- Financial costs such as construction, maintenance and repair,
- Environmental costs in terms of the possible impacts on both bird and fish wildlife,
- Apprehensiveness in terms of interference with shipping industry,
- Recreational concerns primarily related to fishing and boating, and
- Overall aesthetics if wind turbines are located too close to the shoreline.

Conclusion

The efficiency of water wind farms is dependent upon several key factors. First, greater wind speeds are optimal for producing more energy (Gies, 2008). Second, according to the Renewable Energy Research Laboratory (RERL), the number of turbines, how far from shore the turbines are located, and the water depth all play important roles in a wind farm success (RERL, 2010). Consequently, wind speed needs to be considered along with other key factors such as distance to shore and water depth (RERL). Typically, the farther the turbines are from shore, the greater the wind speeds to generate more power. However, the farther the turbines are from shore, the farther the electricity must travel to connect to a power station thus costing more overall (Public Service Commission of Wisconsin, 2009).

In summary, the process of determining optimal site locations for water wind farms is indeed complex. The data required for a truly comprehensive analysis to determine the optimal location for a water wind farm on Lake Michigan is clearly multifaceted. Once a specific location is identified, a more extensive investigation as to the economic and environmental impacts also needs to be conducted to determine a sites full impact upon the area. Additionally, the development of federal and state regulations and laws most likely needs to take place to help guide offshore wind energy into the future. Given the complexity of the site determination process and the economic, environmental and potential legal hurdles that need to be overcome, water wind energy still has the capability to increase and revolutionize the production of clean, renewable, electrical energy in the world.

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