2024 Northern Arizona University Collegiate Wind Competition Project Development

Midyear Report

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Project Sponsor: US Department of Energy and The National Renewable Energy Library

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1 Introduction

Over the course of the semester, the Northern Arizona University WindJax Project Development sub team has worked to gather site and technology data to create this first draft of the proposed hypothetical offshore wind power plant in accordance with the rules stated in the Department of Energy 2024 Collegiate Wind Competition Phase 2 and 3 Rulebook [1]. The following report summarizes the work put in by the sub team accordingly. All figures are condensed to the end of this report as suggested by Appendix D of the rulebook for easier judgement of page limitations.

2 Concept Selection

1.1 Site Selection

The traditional method of engineering concept generation consists of a Pugh chart and a decision matrix but given the nature that there are only 2 concepts to consider, the team is electing to neglect the Pugh chart and only move forward with a decision matrix. The implementation of the Great Lakes will be based on the engineering and customer requirements stated in the QFD located in section 7 titled Tables (table 1). For further insight, the decision matrix is also located in section 7 table 2.1. The weighted criterion of the matrix consisted of average winds speeds at a hub height of 100m, estimated levelized cost of energy (LCOE), interconnectivity, surface area, major cities in the surrounding area, and bathymetry data. Inconclusion, Lake Michigan outscored Lake Superior 85 to 64, respectively. With that being said, the team will now pursue an in-depth analysis based on Lake Michigan.

1.2 Turbine Selection

The team selected six turbines from the top three wind turbine production companies in the US: Vestas, Siemen Gamesa and General Electric. The six turbine selections were analyzed via a decision matrix with weightings created from the team's house of quality. Criteria used for comparing turbines include rotor diameter, cut in and cut out speed, power rating, max possible turbines per 100 square kilometers, rated power output for 100 square kilometers, estimated turbine cost, and port infrastructure requirements. These criteria were developed as simple but effective ways to compare the turbine selections.

Each turbine was scored based on the scoring rubric visible in table 2.2.1 in a decision matrix, visible in table 2.2.2 at the end of this document. The top three turbines - Vestas V174-9.5, General Electric GE150-6, and Siemens Gamesa SG132-5 - will continue a more rigorous analysis and modeling in Furow with full farm data as the team progresses. For this report, the team has selected to pursue the Vestas V174-9.5, as the larger rated power will allow the team to pursue a higher farm power output with fewer turbines, and moving forward will input all the top three turbines to optimize the design.

1.3 Anchor Selection

The team researched both onshore and offshore anchor systems to select the most efficient structure for the site in Lake Michigan. Since our project focuses on offshore wind farm layout, we've concluded that there are two types of anchor structures that are ideal for the conditions in that site. A hybrid or a TLP (Tension Leg Platform) design is the most reliable structure for a wind turbine in that site. The conditions that are present in that location have known factors such as high winds and icing at certain times of the day depending on the season. The team decided these platforms by also setting up Pugh chart and a decision matrix. The Pugh Chart (Table 2.3.1) was set up to compensate factors like how the structure is affected by icing or stability of the structure and the Decision Matrix (Table 2.3.2) was used to account for environmental impacts or cost of installation. This led us to conclude that the structures were optimally fit for the scenario since our wind farm layout does not have over exceeding amount of wind turbine in that location which would increase the cost of building these anchors. The structures in Figure 2.3 give us an ideal design that would make us aware of what to construct and what to avoid on this site.

1.4 Transmission Infrastructure

The results derived from section 2.1 allowed the team to research different points of interconnection through a top-level concept selection utilizing a Pugh chart and decision matrix based off the criteria set by the QFD. The criterion that being considered is the distance from the nearest major city, population of the nearest city, transmission capacity, expected year of retirement, sea life habitats and migration patterns, recreation use of lake, ship traffic map, bathymetry data, wind speed data at a hub height of 100m, and estimated LCOE.

For the Pugh chart, the team has decided on five potential power plant locations for overtaking their existing transmission capacity: Sheboygan – Edgewater Generation Station, WE Energies – Oak Creek Power Plant, University Park Power Station, Point Beach Nuclear Plant, and Consumer Energy – J.H. Campbell Generating Complex. With University Park Power Station randomly assigned as the datum, the Pugh chart tells the team that Sheboygan – Edgewater Generating Station, WE Energies – Oak Creek Power Plant, and University Park Power Station are the top 3 locations to move forward in the decision process, however, given that University Park Power Plant is not retiring by 2030, this is excluded from the decision process and replaced with Consumer Energy – J.H. Campbell Generating Complex. This chart can be referenced in section 7 labeled table 2.4.1.

The next step for the three locations is to integrate them into the decision matrix. After all weight values of the power plants are computed based on the criterion, the team will end up with the best location for the point of interconnection. From table 2.4.2, it is evident that Sheboygan – Edgewater Generating Station is ideal location for the team's offshore wind farm point of interconnectivity.

3 Specific Lease Area

From section 2.1 and 2.4, the team discussed how they arrived to the conclusion that Sheboygan, WI of Lake Michigan is the general location of the hypothetical wind farm. The next step is to specify the leasing area within the lake as part of the project proposal. Figure 3.1 is a line graph that depicts the mathematical equation of Willingness to Pay (WTP) as part of the View Damage Cost explained in reference 3. This variable tells the team how much a resident is willing to pay as an additional cost or willing to accept (WTA) as a discount towards their monthly electric bill based on the specific distance the offshore wind farm is from the shoreline. Since the distance is unknown, the team used MATLAB and assigned the distance as an open array for equation 1 as seen below. From this graph the team has determined that the ideal distance from the wind farm to the shoreline is approximately 27.5 miles. This can be seen in figure 3.2 of section 6. This value will drive the rest of the team's research.

$$WTP\left[\frac{US\ dollar}{month \cdot household}\right] = 27.464 \cdot \ln\left(D_{farmtoshore}\right) - 90.911 = -WTA \qquad [1]$$

For this specific location within the lake, the team will consider other characteristics such as access to transmission, environmental factors, bathymetry data, wind resources, and transportation access. Figure 3.3 illustrates the potential location for the point of interconnection for the wind farm. This map depicts substations and different power plant locations [2]. This will help the team design the plant in regard to the length and cost of transmission lines. Figure 3.4 is an interactive online map that will tell the team where the different fish species live. It also tells the team the species of fish and their designated territories over a period of years [4]. This told the team that there are no fish activity detected at the current proposed lease block. To ensure the team's wind farm is cognitive of the fish species, the team will incorporate a frequency emitting device that redirects and informs the fish of the turbine's presence. Figure 3.5 shows a live feed of current ship traffic within the lake, the density accumulation of the ship traffic, and which routes are most popular [5]. To the team's benefit, the proposed leasing area of the lake is in a location that has the least shipping route density. Figures 3.6 and 3.7 show the popular bird migration patterns and direction during the spring (green) and fall (red) seasons and for the local bat population, respectively. The source also informs the team of the locations within the lake where the birds and bats dwell [6]. The team will use this source to predict when and where the aerial species will fly during the change in seasons. The team is also planning on incorporating an additional frequency emitting device that houses speakers that emit a frequency that is silent to most humans but will make nuisance animals avoid the hazardous area. Figure 3.8 is an interactive map that gives the team the ability to look at the gradient of the bathymetry data within the lake [7]. This will help the team determine the quantity of fixed and floating anchors needed. Figure 3.9 is a map of the United States that show the annual average wind speeds at a specified hub height of 100 meters [8]. This will help the team in determining the potential output the farm will produce and judge the reputability and applicability of the wind resources that the team uses. Reference 9 is an informative website that's lets the team know about three different ports within Sheboygan such as the distance, amount (weight) of cargo shipped, and the main uses of the port. This information will be necessary when planning the construction phase.

4 Preliminary Wind Farm Design

1.5 Site Characteristics

Site characteristics play an important role in the overall design of the wind farm. Therefore, this section will go over wind resource information, wave heights, bathymetry data, weather impacts, transmission and port infrastructure, species in the area, lake activity, and mitigation options based on the teams selected lease area. This analysis will be conducted for the designated lease block depicted in figure 3.2.

Using reference 10, *Great Lake Portal,* this tells the team the current, past, and present wave heights, direction, and duration as well as the ground level wind speeds, gusts, and direction for any point of reference within the lake. For example, at the time of writing this report (Dec. 08, 2023 at 3pm MST), the weather is partly cloudy with a wave height of 6 feet in a north-east direction for an approximate period of 7 seconds. Additionally, the wind is blowing in a north-east direction with speeds of 18 knots. This data will help the team determine the structural integrity of the turbine shaft and anchor design for everyday and extreme weather conditions. Benefiting from the interactive map of resource 7, the team can estimate the water depth of the lease area is approximately 250 to 600 feet deep. To justify these measurements, the team will cross reference figure 4.1.1 (section 7) from source 11 for the Mid-Lake Plateau. The biggest weather concerns the team anticipates with Lake Michigan in the freezing conditions of the winter season. Reference 12 shows an animated map of the ice cover percentage of the Great Lakes bed from 1973 to 2023. An image of the ice cover percentage of Lake Michigan in 2023 is shown in figure 4.1.2. The consensus of this animation states that freeze over within the lease block is relatively negligible with a handful of outlying years. However, the team will still incorporate a cone shaped device at the base of the turbine tower similar to the one show in figure 4.1.3 [13]. The purpose of this cone design is to break the ice layer as it comes into contact with the turbine tower. Given that the location for the point of interconnection is at Sheboygan, WI, the team will utilize reference 14 and 15 to understand the types, lengths, and end destinations of the transmissions line throughout the state shown in figures 4.1.4 and 4.1.5 respectively. Additionally, the team used reference 9 to determine that Port Manitowoc will be the primary location for shipping and on-site construction. Referencing resource 4 tells the team that the sensitive fish population harbors the shoreline and won't be impacted the wind farm. However, the map of reference 5 (figure 3.5) illustrates that the wind farm will interfere with ship traffic lanes. Therefore, the team will need to communicate with the local shipping companies and port officials of an alternate path within the lake.

1.6 Wind Farm Layout

As described in section 2.2, the current selection of turbine is the Vestas V174-9.5 with a rotor diameter of 174 meters, rated power of 9.5MW, and hub height of 110 meters. The team's current design of leasing area, as shown in figure 3.2, contains approximately 100 square kilometers and the boundary is approximately represented with the coordinates West: 43.719, East: 43.717, North: -87.118, South: -87.140. With turbines spaced 5 diameters (870 m) apart opposite the prevalent wind direction, and 8 diameters (1392 m) apart in the prevalent wind direction, the team can fit 64 turbines in the current proposed leasing area. This is depicted in figure 4.2.1, with circles representing turbine placement. The circles are *not* to scale for the actual rotor diameters and have been enlarged for clarity in viewing. The power rating of this quantity of turbines well surpasses the current production of the Edgewater Generation Facility, the planned grid interconnection site as described in section 2.4. This allows the team confidence in future optimization through descaling the size of the project.

As described in section 2.3, the current foundation type is selected to be a TLP structure since it's the most effective design that can withstand icing conditions and stability due to probable wind conditions in that site area. Even if a TLP design is not preferable in that location, a hybrid is like a TLP but will have specific custom anchor designs implemented which can add cost to constructing it. A TLP can also have mooring lines attached to it which can be adjusted for specific site locations like Lake Michigan and that it will not affect any of the lakebed in that area.

The next prospect of maintaining offshore wind turbines is analyzing when a turbine needs maintenance and how to maintain it since it can affect efficiency and cost through time. The estimated time to check on a wind turbine is two to three years on average. This can give us ideal preparation in having a vessel deployed near the site for maintenance reasons. Resource 29 talks about Windea Jules Verne service operations vessel (SOV) which can be the next step in applying this type of vessel in Lake Michigan.

In terms of fully connecting the wind farm, the team is going with a traditional design where the transmission cables are suspended in the water for both the floating and fixed anchor designs. Once the turbines are connected in series, the transmission lines will be buried at the base of the offshore substation. Through the trenched lines, it will go directly to the onshore substation. This is where the team will connect to the grid by taking over Edgewater's Generation Station transmission capacity. Since there is no suitable substation onshore, the team is expecting to construct infrastructure to allow safe and easy transfer of power. This phase of the project will be in conjunction with Wisconsin Public Service Corp, the local utility company, and the corresponding utility services to settle upon a power purchase agreement.

The team's ultimate goal for the integration of the wind farm in Sheboygan, WI is to ensure that the stake holders, clients, residents, and the corresponding government parties are fully aware of the intention and purpose of the farm. Therefore, the team will partner with the state of Wisconsin, city of Sheboygan, and Edgewater Generation Station to ensure that all state and local rules and regulations are met. *Public Service Commision of Wisconsin - Wind Siting Rules*, will be used to understanding the notice filing, local wind application filing requirement, commission protocols, and additional wind energy information and staffing contact information.

5 Conclusion

The team is confident moving forward in our ability to optimize the size, production, and cost of this project. Next steps that the team intends to take are to analyze the power production curve of the leasing area in Furow with slight adjustments to design given the wind resource and turbine data. The team plans to further develop a cost analysis using the System Advisor Model and JEDI to ensure that both power output and cost of the project are optimized.

6 Figures

Note: All figures containing a red box represents the teams selected lease block (not to scale) within Lake Michigan

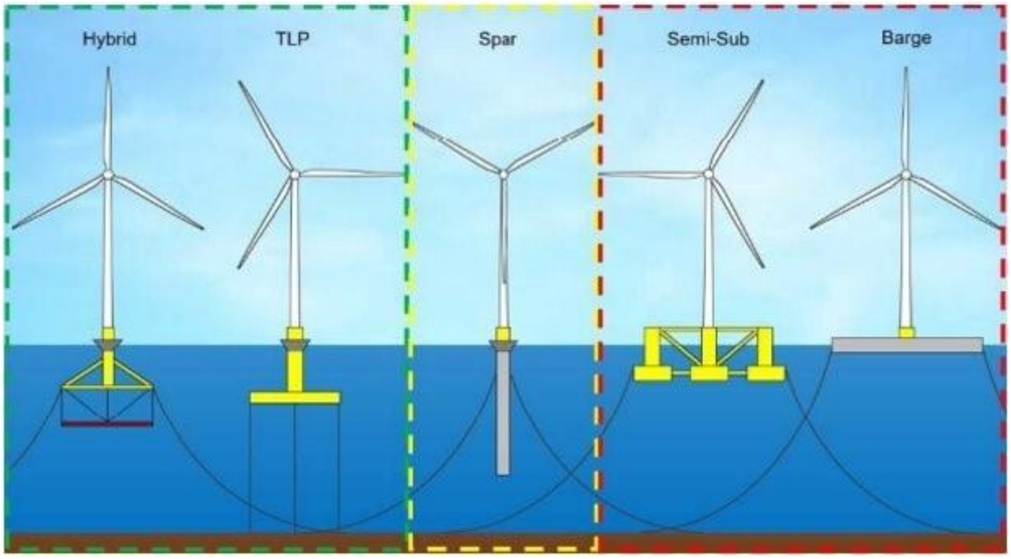

Figure 2.3: Diverse types of anchor designs

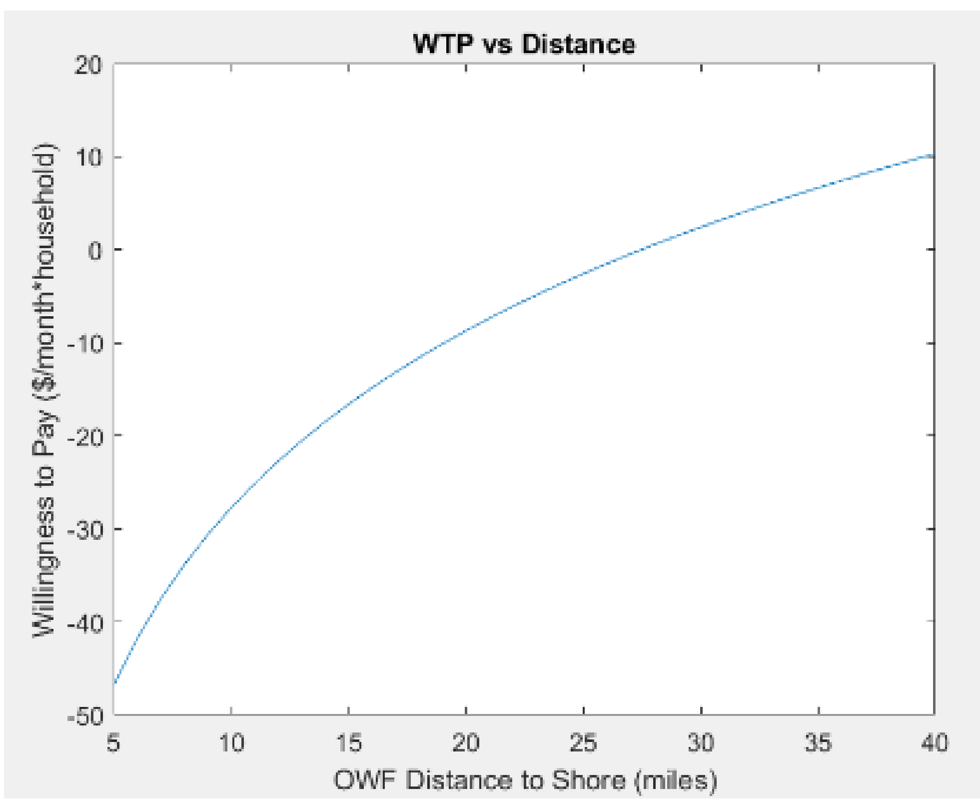

Figure 3.1: Willingness to pay vs Farm distance [3]

Figure 3.2: Leasing area adjacent to Sheboygan, WI

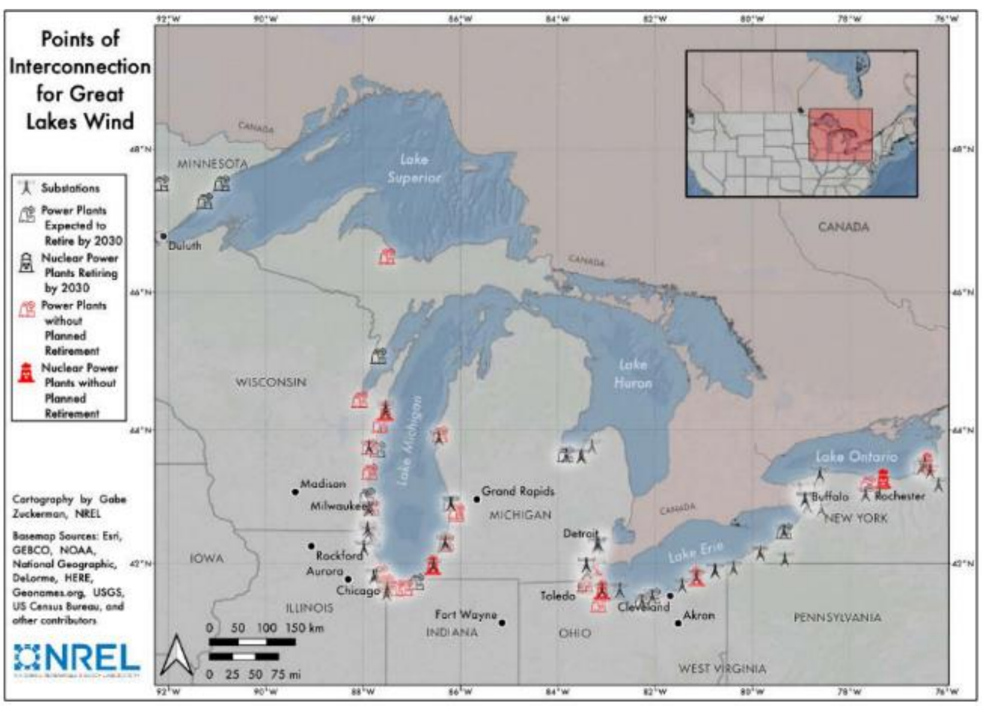

Figure 3.3: Point of interconnection of Great Lakes Wind [2]

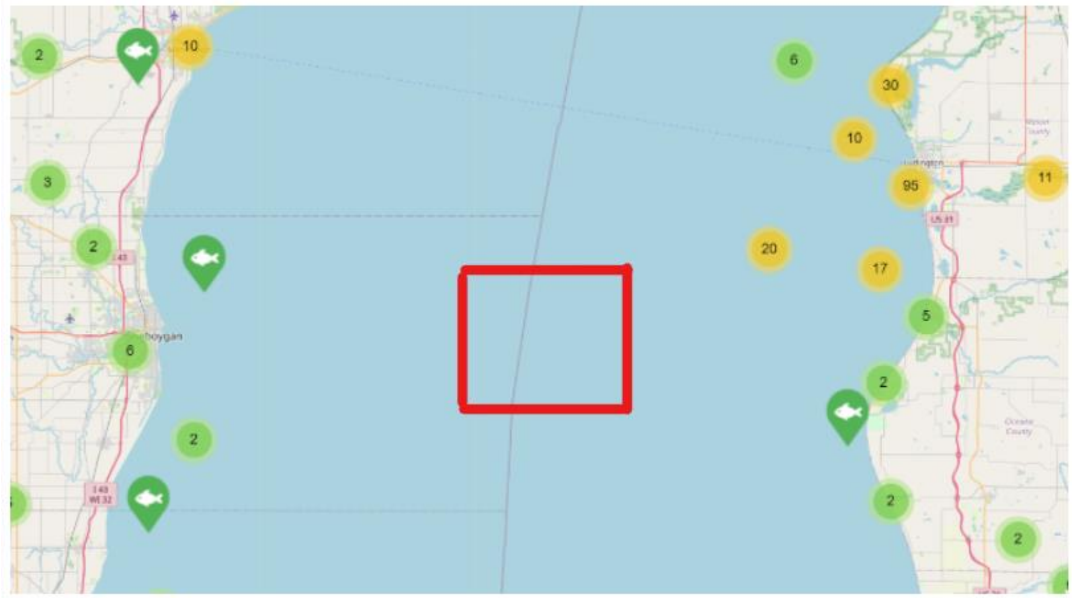

Figure 3.4: Interactive map of fish habitats within Lake Michigan [4]

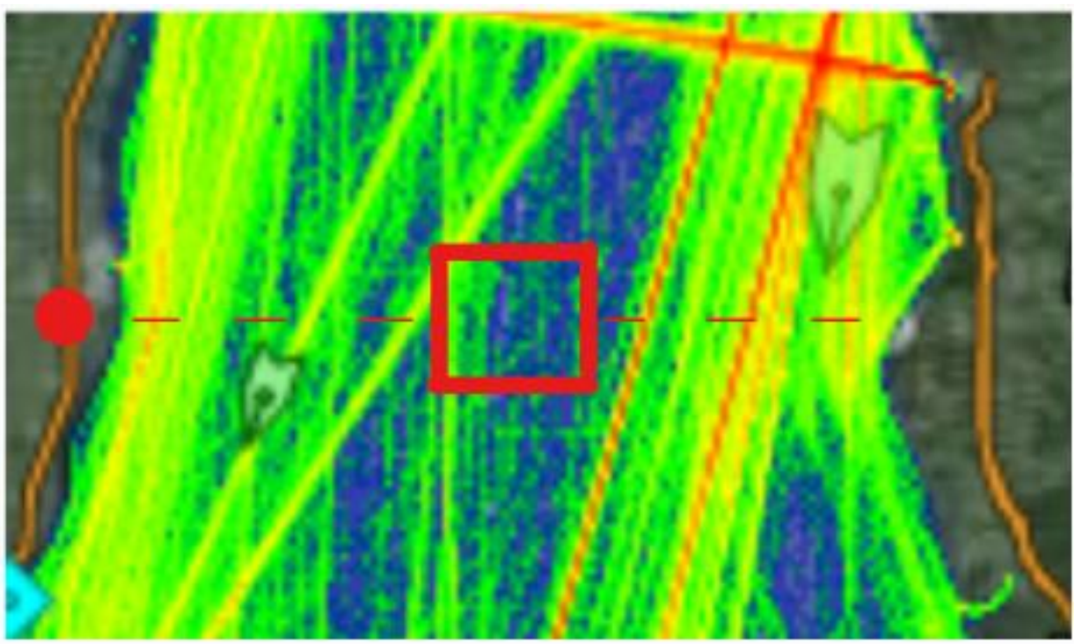

Figure 3.5: Ship traffic map with respect to the Sheboygan, WI [5]

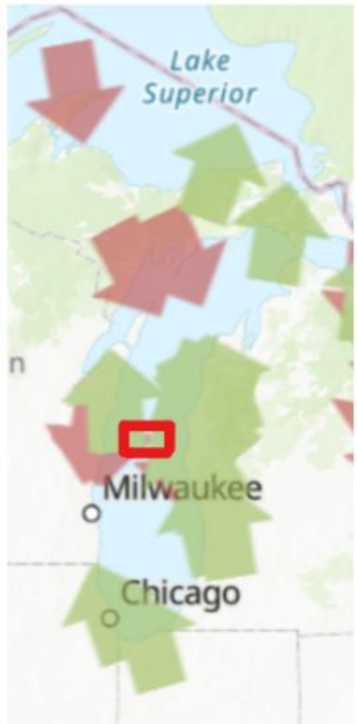

Figure 3.6: Bird migration directions within Lake Michigan [6]

Figure 3.7: Local bat populations within Lake Michigan [6]

Figure 3.8: Interactive bathymetry map within Lake Michigan [7]

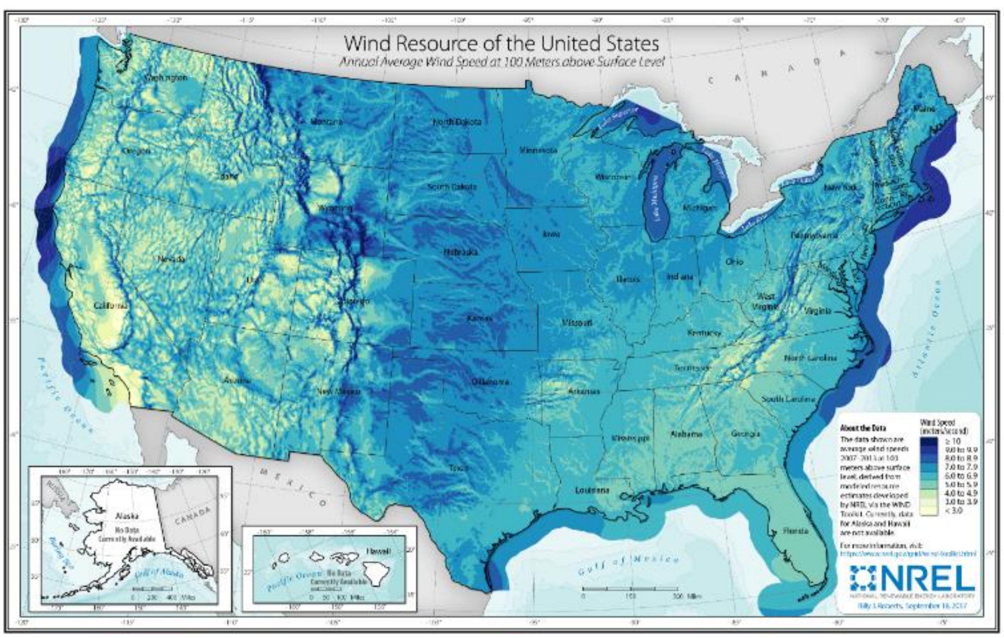

Figure 3.9: Annual average wind speeds at 100m above sea level [2]

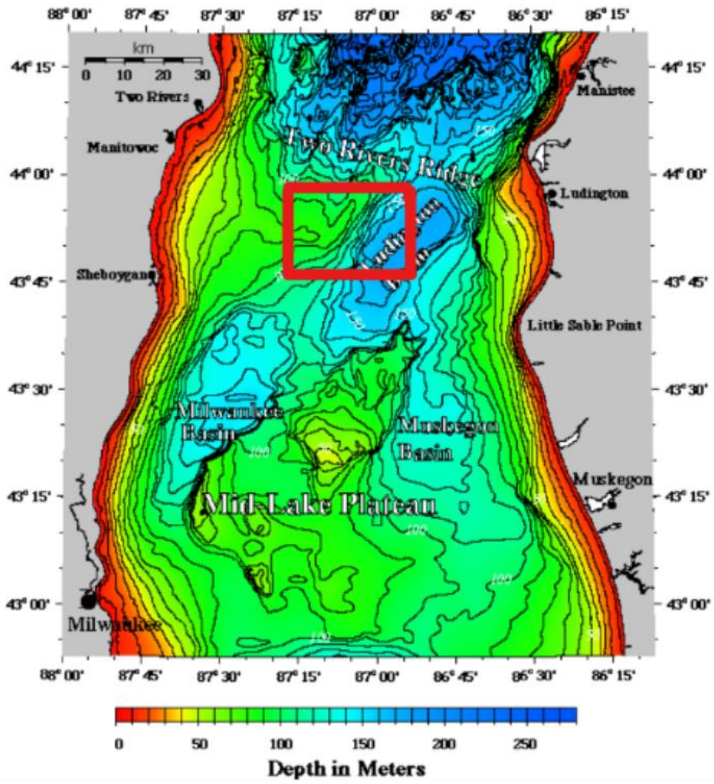

Figure 4.1.1: Mid-Lake Plateau water depth within Lake Michigan [11]

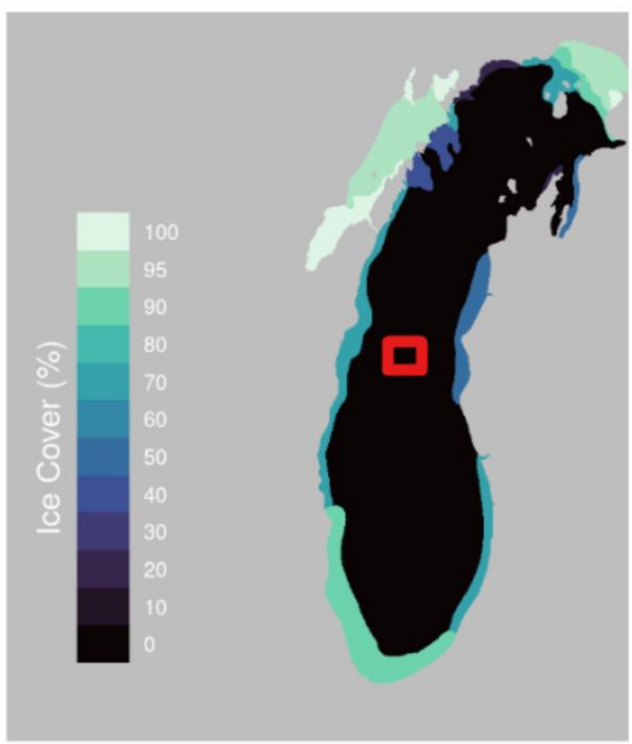

Figure 4.1.2: Ice cover percentage of Lake Michigan in 2023 [12]

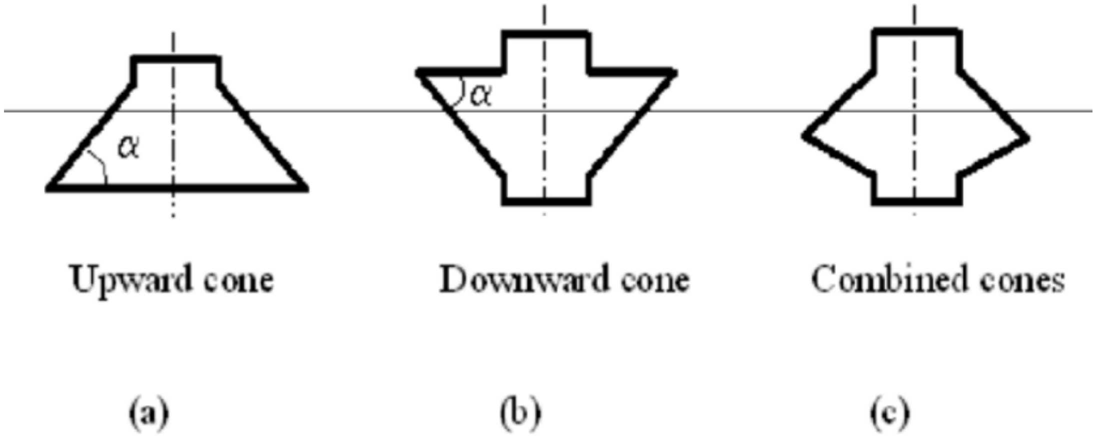

Figure 4.1.3: Ice breaking cone design [13]

Figure 4.1.4: Point of interconnection transmission lines (solid red) with in Sheboygan, WI [14]

Figure 4.1.5: Transmission lines throughout the state of WI [15]

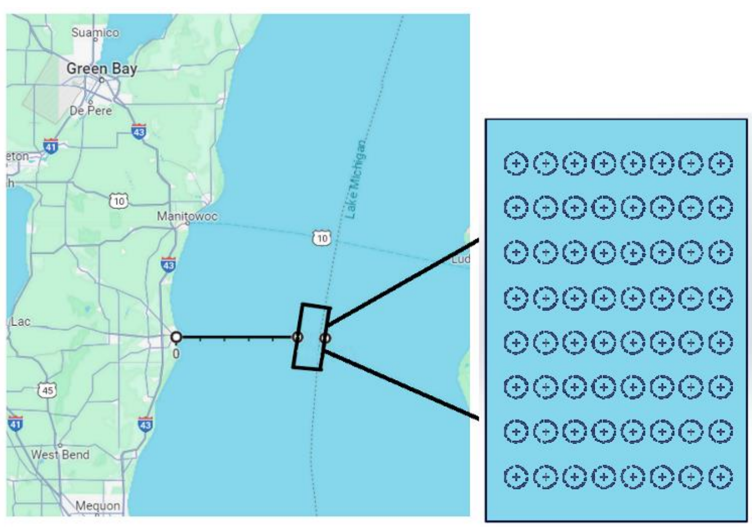

Figure 4.2.1: Current proposal for turbine spacing within the leasing area

7 Tables

1: low, 5: high Customer importance rating (for full competion points)	Desired direction of improvement (↑,0,↓) Engineering Requirements (How's) → Customer Requirements - (What's) ↓	↑ Area of Leasing Block (km^2)	↓ Levelized Cost of Energy ($/kWhr)	↓ Capital Expenditures ($)	↓ Operational Expenditures ($/year)	↑ Farm Power Output (150 MW)	↑ Wind Data (85-140m height)	↑ Bathymetry Data (m)	↑ Weather Data (WindSpeed max for 100yr storm, and frequency below freezing)	↑ Port Infrastructure (area of port, machinery available)	↑ State/Country Policies	↑ Species Migration Paths (km^2 mapped)	↑ Shipping Routes (mapped)	↑ Power Grid Utility Line Connections (<80km to plant)	↑ Community Usage Data (<100 people in area monthly)
5	20 year lifespan	0	0	0	0	0	5	5	9	5	5	0	0	0	1
5	Siting Selection	9	0	9	0	0	9	9	9	9	5	9	9	5	9
5	Technology Selection (Turbine, Anchor, Energy Transmission)	5	9	9	9	9	9	9	5	9	5	5	0	5	0
5	Development and Technical Integration Plans	9	5	9	5	5	1	0	0	9	9	5	9	9	5
5	One other generation, storage, or end-use technology	5	5	5	5	5	0	9	5	5	5	5	1	5	1
4	Harm mitigation strategies for affected ecosystems	9	0	5	5	0	5	5	1	0	5	9	5	0	1
3	Local Community Impact	1	1	0	1	5	0	1	1	5	5	1	5	5	9
5	Financing Plan - annual costs, market incentives, etc	5	9	9	9	9	5	0	0	5	1	0	1	1	1
4	Cost of Energy and cash flow analysis	1	9	9	9	5	5	0	0	5	5	0	0	5	0
3	Annual Energy Production	5	1	0	0	9	9	1	5	0	0	1	0	0	0
5	Bid for potential Lease Block	9	9	9	5	5	5	0	0	5	5	0	0	1	0
	Technical importance score	228	179	261	179	155	165	138	122	225	205	134	135	140	116
	Importance %	10%	8%	11%	8%	7%	7%	6%	5%	9%	9%	6%	6%	6%	5%
	Priorities rank	**2**	**5**	**1**	**5**	**8**	**6**	**6**	**8**	**1**	**2**	**5**	**3**	**9**	**14**

Table 1: House of Quality (QFD)

		Lake Michigan		Lake Superior	
					
Criteria	Weight	Score	Weighted	Score	Weighted
Wind Speeds	20	0.9	18	0.8	16
LCOE	20	0.9	18	0.75	15
Interconectivity	20	0.7	14	0.2	4
Surface Area	15	0.9	13.5	0.8	12
Major Cities	15	0.9	13.5	0.7	10.5
Bathymetry	10	0.8	8	0.65	6.5
Total: 100			85		64

Table 2.1: Site selection decision matrix

Turbine Scoring Explained:										
Rotor Diamete (m):	0-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300
Score	1	2	3	4	5	6	7	8	9	10
Cut In Speed (m/s)	4.1-5	3.1-4	2.1-3	1.1-2	0-1					
Score	2	4	6	8	10					
Cut Out Speed (m/s)	15-20	21-25	26-30	31-35	36-40					
Score	2	4	6	8	10					
Power Rating (MW)	0-1.5	1.6-3	3.1-4.5	4.6-6	6.1-7.5	7.6-9	9.1-10.5	10.6-12	12.1-13.5	13.6-15
Score	1	2	3	4	5	6	7	8	9	10
Max Possible Turbines in 100km square	0-10	.11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Score	1	2	3	4	5	6	7	8	9	10
Rated Power Output for 100km^2 (MW)	200-280	281-360	361-440	441-520	521-600					
Score	2	4	6	8	10					
Turbine Cost ($)	>15 mil	14.2-15	13.4-14.1	12.6-13.3	11.8-12.5	11-11.7	10.2-10.9	9.4-10.1	8.6-7	<7 mil
Score	1	2	3	4	5	6	7	8	9	10
Port Infrastructure Requirement	1a	2a	3a	4a						
Score	2.5	5	7.5	10						

Table 2.2.1: Turbine selection criterion scoring

		V236-15		V174-9.5		GE150-6		SG132-5		SG200-11		SG222-14	
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Rotor Diameter	9.76	8	0.780488	7	0.682927	5	0.487805	5	0.487805	7	0.682927	8	0.780488
Cut in Speed	4.88	6	0.292683	6	0.292683	6	0.292683	8	0.390244	6	0.292683	6	0.292683
Cut out Speed	7.32	8	0.585366	4	0.292683	4	0.292683	6	0.439024	4	0.292683	4	0.292683
Power Rating	4.88	10	0.487805	7	0.341463	4	0.195122	4	0.195122	8	0.390244	10	0.487805
Max Possible turbines/100km^2	2.44	3	0.073171	6	0.146341	8	0.195122	10	0.243902	4	0.097561	4	0.097561
Rated Power Output for 100km^2 (MW)	21.95	6	1.317073	8	1.756098	8	1.756098	8	1.756098	6	1.317073	8	1.756098
Turbine Cost	19.51	4	0.780488	9	1.756098	10	1.95122	10	1.95122	8	1.560976	5	0.97561
Port Infrastructure Requirement	29.27	2.5	0.731707	7.5	2.195122	10	2.926829	10	2.926829	5	1.463415	2.5	0.731707
Total			5.04878		7.463415		8.097561		8.390244		6.097561		5.414634

Table 2.2.2: Turbine selection decision matrix

SubDesign:										
	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9	Option 10
	Gravity-Base	Tripod	Mono-bucket	Mono-pile	Jacket	Hybrid	TLP	Spar	Semi-Sub	Barge
Criteria										
Price	+	-	+	+	+	-	-	+	+	+
Weight	-	+	-	+	-	+	+	+	-	-
Stable	+	+	-	-	+	+	+	-	+	+
Material	+	-	+	+	-	-	+	+	+	+
Life expentency	-	+	+	-	+	+	+	-	-	-
Icing	-	+	-	-	-	+	+	-	-	-
+	3	4	3	3	3	4	5	3	3	3

	0	0	0	0	0	0	0	0	0	0	0
	-	3	2	3	3	3	2	1	3	3	3
	Total	0	2	0	0	0	2	4	0	0	0

Figure 2.3.1: Achor selection Pugh chart

		Option 1		Option 2		Option 3		Option 4		Option 6	
		TLP		Hybrid		Gravity-Based		Tripod		Monobucket	
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Technical Feasability	3	8	24	4	12	9	27	5	15	9	27
Cost	6	7	42	7	42	4	24	2	12	8	48
Safety	8	8	64	7	56	7	56	7	56	7	56
Environmental Impact	7	9	63	8	56	3	21	4	28	2	14
Installation	1	3	3	8	8	6	6	8	8	7	7
Ports	4	4	16	8	32	4	16	8	32	6	24
Heavy Lift Eqiupment	5	8	40	8	40	3	15	4	20	6	30
Modeling	2	7	14	7	14	8	16	9	18	8	16
Total			266		260		181		189		222

Table 2.3.2: Anchor selection decision matrix

Power Plant / Cirteia	Sheboygan - Edgewater Generating Station	WE Energies - Oak Creek Power Plant	University Park Power Station	Point Beach Nuclear Plant	Consumers Energy - J.H. Campbell Generating Complex
Distance from nearest major city	-	0	Datum	0	0
Population of the nearest city	-	-		-	-
Transmission capacity	+	+		+	+
Expected year of retirment	+	+		-	-
Sea life habitats and migration pattern	-	-		-	-
Recreational use of lake	+	-		-	+
Ship traffic map	+	-		+	+
Bathymetry data	0	0		0	-
speeds data at a hub height of 100m	0	0		0	0
Estimated levelized cost of energy	0	0		-	-
+	4	2	0	2	3
0	3	4	0	3	2
-	3	3	0	5	5
Σ	1	-1	0	-3	-2

Figure 2.4.1: Transmission infrastructure Pugh chart

		Sheboygan - Edgewater Generating Station		WE Energies - Oak Creek Power Plant		Consumers Energy - J.H. Campbell Generating Complex	
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted
Distance from nearest major city	15	0.7	10.5	0.9	13.5	0.8	12
Population of the nearest city	20	0.9	18	0.9	18	0.6	12
Transmission capacity	10	0.9	9	0.4	4	0.2	2
Expected year of retirment	5	0.7	3.5	0.8	4	0.5	2.5
Recreational use of lake	5	8	40	6	30	4	20
Sea life habitats and migration pattern	10	0.9	9	0.6	6	0.7	7
Ship traffic map	10	0.6	6	0.5	5	0.75	7.5
Bathymetry data	5	0.85	4.25	0.9	4.5	0.9	4.5
Average wind speeds data at a hub height of 100m	5	0.85	4.25	0.85	4.25	0.85	4.25
Estimated levelized cost of energy	15	0.9	13.5	0.9	13.5	0.85	12.75
Total			118		102.75		84.5

Figure 2.4.2: Transmission infrastructure decision matrix

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