2024 Northern Arizona University
Collegiate Wind Competition
Project Development Sub Team

Initial Design Report

Alexander Longoria – Data Validation Engineer

David Perez – CAD Engineer

Samantha Russell – Logistics Manager and Rules Specialist

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

Faculty Advisor: Dr. David Willy

DISCLAIMER

EXECUTIVE SUMMARY

The U.S. Department of Energy’s (DOE) Wind Energy Technologies Office’s (WETO) Collegiate Wind Competition (CWC) welcomes 35 interdisciplinary teams of undergraduate students from a variety of notable universities across the nation to compete in four contests. Northern Arizona University WindJax’s are split into 2 sub-teams: Turbine Design and Project Development. The nature of this report will focus on the Project Development team as they are tasked to research wind resource data, transmission infrastructure, and environmental factors to create a site plan and financial analysis for a hypothetical offshore wind farm. Some key factors the team will need to consider are physical site characteristics, infrastructure, turbine selection, ports, transmission, grid integration, environmental and wildlife impacts, and the coexistence between the residence and the turbines.

New to this year, the CWC encourages students to incorporate offshore wind energy generation as a feature to a hybrid power plant. This allows students to consider development and operation opportunities for grid benefits, alternative forms of market participation and mutual agreements, and a vast array of technological solutions.

At the time of writing this report, Northern Arizona University WindJax’s Project Development team has progressed through the phase 1 selection and is preparing to be evaluated for the phase 2 cycle which ends at the end of Fall 2023. The team also accomplished an in-depth analysis of customer and engineering requirements, mathematical modeling that was backed by a literature review, and concept generations and evaluations that was determined by engineering calculations. The results of each analysis were checked and verified through the faculty advisor. The Project development team's next step is to model the hypothetical offshore wind farm using various online resources and software.

This report will discuss the team's efforts in designing, analyzing, and modeling an offshore wind farm based on the 2 Great Lake locations (Lake Michigan and Lake Superior). Lease block size, population and environmental impacts, current utility support, turbine selection, and anchor design are several key factors that will be examined through this report to determine the ideal location, farm size, financial report, and power output.

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1 BACKGROUND

The Project Development goal, as laid out by The Department of Energy – the project sponsor – is to create a fully-fledged plan for a hypothetical offshore wind farm to participate in the 2024 Collegiate Wind Competition. With this, The Department of Energy (DOE) has communicated how the team will be scored compared to the other 35 competing university teams via the competition rulebook [1]. This competition gives applicable experience to engineers entering the field into project development and management. Applying hypothetical site development plans towards this project will address real world research questions that could potentially help wildlife habitability and migration, environmental protection, and the growing demand for clean energy. To this end, the Project Development team will need to evaluate site data, electrical grid data, and existing technology data to create a site development and maintenance plan. Alongside this, the team will need to analyze finances and prove that the hypothetical wind farm would be realistic. Further detail in the expectations of the DOE are as follows:

- Physical site characterization like assessing freshwater icing challenges, soft bed lakebed sediments, shallow bedrocks, and/or heavy metals in sediments.
- Consideration of access to infrastructure or ports, accounting for vessel constrictions
- Supply chain needs to manufacture, transport, install, and maintain equipment.
- Electric grid interconnection and integration, accessible electric power network and handling power capacities
- Accounting for no impact in wildlife and environment, migration, fish ecology, aquatic resources, etc.
- Assessing coexistence with residents and tribes in the U.S. and Canada
- Incorporate offshore wind energy generation as part of a hybrid power plant for development and operation in ancillary grid benefits.
- Market participation offtake agreements and multi technology solutions

1.1 Project Description

In this year's Collegiate Wind Competition (CWC24), 35 teams will be selected to compete for a greater engineering career pathway to be implemented towards knowledge of wind energy's potential clean energy future. The competition is divided into four contests and three phases: Turbine Design, Turbine Testing, Project Development, and Connection Creation. The first phase happens when all 35 teams have submitted their motivations in entering the competition. Phase two requires 12 teams to perform in reports and videos of how well they achieved competition objectives in the four contests. The third phase is the final where the team has performed and met industry standards along with completing a final report.

1.2 Deliverables

The Project Development team is required to present three presentations for the first semester and submit two reports: one for the mid-semester and one for the final semester for the 476C course. Towards the end of the semester the team is required to build a virtual wind farm using wind resource programs that represent building a future turbine in the great lakes. The final submission is also important for information of each engineer that was part of this project stating information about them and the project in a website.

The midyear report is a submission focusing on team's outreach goals, recruitment, and sponsorship strategies, and different plans for achieving these goals, this is around five pages long. The section of the report is directly correlated to the final metrics report which details all of the requirements even the amount of photos that need to be taken.

The project development team is also required to turn in a final report to the reviewers that specifically focuses on a yearlong project. Details include site selection, financial analysis, discussuion of optimization process, and a bid for a lease.

1.3 Success Metrics

The success of this project accounts for key aspects of a wind farm siting and the activities relating to project development. Understanding how wind resource data is calculated, estimating performance, project economics, bathymetry, environmental issues, transportation constraints, transmission design, permitting requirements, turbine technology, and performance variables (e.g., wakes, turbine availability, and site-specific losses). Understanding these long-year key aspects are crucial to deliver customer requirements and engineering requirements like incorporating one other generation, storage, or end-use technology that can be added to the offshore wind turbine system (hybrid). Concluding the cost of energy is also important to also compensate a 20-year life expectancy. Getting involved with communities (connection creation) is also important for us to consider getting the right amount of info.

2 REQUIREMENTS

In order to ensure that the team meets the expectations of the client, a thorough breakdown of the client's desires and engineering measurements to meet them is required. The team did this by creating a House of Quality (HoQ) or Quality Function Deployment (QFD). This allows the team to understand how important each engineering standard is to the overall project from the consideration of the client/customer wants. These engineering requirements will help the team to quantify different aspects of design and pick the best design overall for the client. The Project Development team found eleven customer requirements and created twelve related engineering requirements. These requirements have undergone changes since their creation, and will continue to undergo changes as the team learns more. This section contains the most up-to-date version.

2.1 Customer Requirements (CRs)

The Department of Energy supplied their expectations via the Collegiate Wind Competition 2024 Phase 2-3 Rules Document [1]. This document was used to define the customer requirements. Few of these requirements have quantities associated with them, and so the team will need to rely on research of current wind turbine power plants to guide the project.

The requirements from The Department of Energy largely include selections for the team's hypothetical power plant, and justification for those selections. The team must select technology to be used and a site for the offshore wind farm in the great lakes. The technology selection is for existing technologies and designs of offshore wind turbines, anchor systems, energy transmission lines, and one other generation, storage, or end use technology. The site selection refers to the location of the offshore farm, both the decision on the lake, it resides in as well as the exact location within that lake. To support and inform these selections The Department of Energy also requires a development and technical integration plan, which informs how the power plant would be installed, harm mitigation strategies for affected ecosystems, which would ensure that the power plant is not causing undue stress to endangered species or fragile ecosystems nearby, and a financing plan, which includes annual costs, cost of energy and flow analysis, and market incentives to prove that the proposed power plant is profitable. Additional customer requirements include a 20-year lifespan for the power plant, an analysis of community impact, and a bid for a potential lease spot.

2.2 Engineering Requirements (ERs)

The team created engineering requirements guided by the needs of the customer requirements. As the client did not specify many values, the Project Development team is using values as indicated by the team's advisor, Dr David Willy, and turbine data as a starting point. Some of these values are expected to change as the team becomes more acquainted with the data. These requirements include several types of data, including bathymetry (water depth) in meters, wind speed in meters per second, weather data in which the team will focus on extreme weather events for high wind speeds as well as frequency that the lake is expected to be frozen yearly, species migration paths and shipping routes in which the team will review mapped square kilometers in reference to potential plant sites with the goal of being completely outside those zones. The team included further data for the engineering requirements that include community usage measured in population monthly usage with a goal of less than 100 people, power grid data measured in distance from power plant to substation with a goal of less than 80 km, and finally state and country policies. The final engineering requirements utilize all the prior mentioned data. These requirements are plant power output with the minimum goal of 150 MW, levelized cost of energy measured in dollars per kilowatt-hour, and area of leasing block measured in square kilometers. Typical development plans are given leasing blocks, but The Great Lakes do not as of yet have any such blocks.

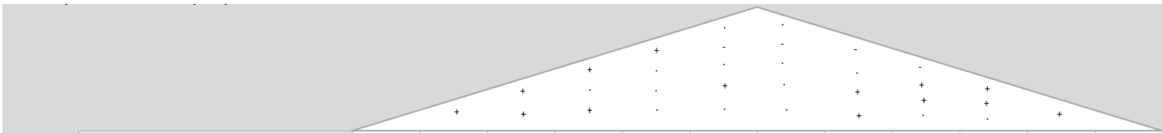
2.3 House of Quality (HoQ)

For ease of viewing, the benchmarking "room" is separated into Figure 2.3.1, below. The benchmarking is covered further in Section 3.1 . The ratings given to each benchmarking are the team's assessment of how well each group met this year's customer requirements.

Benchmarking and competitive evaluation (1: low, 5: high)		
NAU 2022	NAU 2023	Pennsylvania State University's (PSU) 2023
5	4	5
5	3	5
4	3	5
4	4	5
1	1	1
4	3	4
5	4	3
5	3	5
5	3	5
5	4	5
4	4	4

Figure 2.3.1: House of Quality Benchmarking Room

The next page contains the CWC24 Project development House of Quality in Figure 2.3.2. Each engineering requirement was given a rating of how well it relates to the customer requirement. A rating of zero is unrelated, a rating of one is a weak relation, a rating of five is a moderate relation and a rating of nine is a strong relation to the customer requirement. From this, some simple math is done to see which of the engineering requirements scored highest, and what the team needs to focus on in more depth. The highest rated requirements are the area of the leasing block and port infrastructure. The percentages of importance from this House of Quality inform later sections and decisions made for design.



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)	Farm Power Output (150 MW)	Wind Data (85-100m 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, connection type)	Community Usage Data (<100 people in area monthly)
		↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
5	20 year lifespan	0	0	0	5	5	9	5	5	0	0	0	1
5	Siting Selection	9	0	0	9	9	9	9	5	9	9	5	9
5	Technology Selection (Turbine, Anchor, Energy Transmission)	5	9	9	9	9	5	9	5	5	0	5	0
5	Development and Technical Integration Plans	9	5	5	1	0	0	9	9	5	9	9	5
5	One other generation, storage, or end-use technology	5	5	5	0	9	5	5	5	5	1	5	1
4	Harm mitigation strategies for affected ecosystems	9	0	0	5	5	1	0	5	9	5	0	1
3	Local Community Impact	1	1	5	0	1	1	5	5	1	5	5	9
5	Financing Plan - annual costs, market incentives, etc	5	9	9	5	0	0	5	1	0	1	1	1
4	Cost of Energy and cash flow analysis	1	9	5	5	0	0	5	5	0	0	5	0
3	Annual Energy Production	5	1	9	9	1	5	0	0	1	0	0	0
5	Bid for potential Lease Block	9	9	5	5	0	0	5	5	0	0	1	0
	Technical importance score	228	179	155	165	138	122	225	205	134	135	140	116
	Importance %	12%	9%	8%	8%	7%	6%	12%	11%	7%	7%	7%	6%
	Priorities rank	**1**	**4**	**6**	**4**	**6**	**8**	**1**	**2**	**5**	**3**	**7**	**12**

Figure 2.3.2: House of Quality

3 Research Within Your Design Space

3.1 Benchmarking

To satisfy the requirements that are set by the DOE, the Project Development team will reference Pennsylvania State University's (PSU) 2023 performance are they were second overall and first in the project development category. The team can utilize this reference for the structure of the analyses and selection consideration. The team will also reference Northern Arizona University (NAU) 2022 submission for their second overall ranking. The team can utilize NAU's 2022 report as a basic outline in order to improve upon the areas that did not exceed in their respected category.

To revolutionize this year offshore wind farm, the Project Development team has examined three components of the system on a power plant level to determine which components can be altered to consider different state-of-the-art features. Those three plant features will be the utilization of current power plants that are retiring within close proximity of the Great Lakes, optimization of power generated based on the turbine parameters, and an ice preventative design.

The importance of considering retiring plants is to lower cost and time spent on the development of the plant. This will also allow the team to interconnect with the preexisting infrastructure that is providing energy to major cities. The goal of this project is to generate as much power as possible while keeping other components low such as the levelized cost of energy (LCOE). This is directly related to the wind turbine based on the number of turbines, hub height, farm spacing, and distance from shore. Considering these factors will ensure the team's design meets the client's parameters. Lastly, ice is an environmental factor that is still being researched to date. Being that both Great Lakes are susceptible to freezing conditions, the team is focused on designing a turbine tower and anchor system that is capable of surviving these conditions.

Sections 3.2 and 3.3 are provided to show the team's literature research of the power plants state-of-the-art feature on a sub level basis that is then followed by a mathematical analysis to justify the relevance of the design.

3.2 Literature Review

3.2.1 Site Selection – Alexander Longoria

The purpose of an in-depth analysis for Site Selection is to determine which of the Great Lakes is the ideal location for the offshore wind farm. To further explain, this section will go over some of the references used to help the team make that decision.

Global Great Lakes: Lake Superior and Lake Michigan [2]

Reference 1 is an online resource that is backed by the University of Minnesota Duluth's Large Lake Observatory. This source will be used to understand the numerical characteristics of the great Lakes such as the area, volume, population, and retention time of the water.

Protecting Michigan's Inland Lake: A Guide for Local Government [3]

Reference 2 is a guidebook published by michigan.gov titled. This guidebook was drafted to help citizens and officials understand the benefits of the inland lakes, the regulations that govern them, and the opportunities for locals to help protect these lakes.

Lake Superior Shoreland Lot Development Requirements [4]

Reference 3 coincides with rules and regulations from reference 2. This document focuses on the site plan standards that were derived by the corrosive properties of the water and the undercuts of the rocks from the waves. These references will be used to understand the laws and requirements of building infrastructure within the lakes.

Investment cost and view damage cost of siting an offshore wind farm: A spatial analysis of Lake Michigan [5]

Reference 4 will give the team a detailed understanding of the factors that are considered when estimating the initial costs of an offshore wind farm. This article provides the team with all the necessary equations to solve variables such as the Willingness to Pay, Annual View Damage Cost, and the Net Present Value View Damage Cost based on the distance the turbine is from the shoreline.

Lake Michigan and *Lake Superior [6]*

Reference 5 will be coming from the same online resource, greatlakes.guide. Adhering to the Lake Michigan and Lake Superior tabs, the author goes into depth about some of the current problems each lake is facing and how the community benefits from the lakes.

Border Flows: A Century of the Candain-American Water Relationship [7]

Reference 6 is a downloadable pdf book that discusses the relationship of Canada and the United States in regards the water resources and distribution. This book is an important read if the team chooses to consider Lake Superior for the location of the offshore wind farm. Approximately ¼ of Lake Superior is Canadian territory and the other ¾ is American territory. With that being said, if the team decides to populate turbine on the Canadian side, it would be important to understand the history of the two neighboring countries in order to maintain mutual alliance.

Cape Spin: An American Power Struggle [8]

Reference 7 is a documentary film about Americans first ever proposed offshore wind farm, Cape Wind. In this film, they talk about the 10-year struggle Jim Gordon faced because of his 130 wind turbine proposal. The team will be able to utilize this documentary to understand some of the negative backlash received in order to prevent ethical issues within the community.

Great Lakes Wind Energy Challenges and Opportunities Assessment [9]

Reference 8 is a document published by NREL. From this resource, the team will be able to find relevant graphs and information directly related to this year's project. In terms of site selection, this document will drive a lot of the decision and research questions.

3.2.2 Turbine Selection – Sam Russell

Integral to wind power plant output is the turbine that is used. Consideration needs to be given to turbines height, rotor and tower size, optimum spacing requirements, cost, and assembly needs. The following references provide guidance on how best to choose a turbine, as well as provide various turbine specifications.

Offshore Wind: A Comprehensive Guide to Successful Offshore Wind Farm Installation [10]

This source, as suggested by the title, is a guide of offshore wind farm installation. The book is a self-proclaimed guide for project developers and financers, specializing in overcoming challenges associated with wind power plant. This book is referenced in the turbine selection process to give insight into the considerations necessary for turbine installation, transportation to site, and slight cost analysis.

"Wake effect in wind farm performance: Steady-state and dynamic behavior" [11]
This research study shows the importance of turbine spacing with consideration for the wake of the wind. It aims to provide a "rule of thumb" for generalized calculations before full data is known for the power plant. The team references this source in order to make appropriate considerations regarding the turbine spacing.

"Wake effects of large offshore wind farms identified from satellite SAR" [12]
This article reviews the effect of large-scale offshore wind farms on local wind after it passes through the farm. The researchers found that mean wind speeds had decreased eight to nine percent. The article discusses effects as far as twenty kilometers behind the wind farm. This source will be used to consider the turbine's effects as they relate to migration pathways, and will be used to aid in harm reduction plans.

Wind Energy Explained: Theory, Design and Application: Chapter 9: Wind Turbine Siting […] [13]
Chapter nine of the Wind Energy textbook delves into micro siting, introductory aspects of power plant design, and power integration. The team utilized this source to validate source [11] in basic spacing requirements. The team will continue to utilize various sections of this chapter moving forward, as it covers many topics that the project development team will need to understand.

"GE, Vestas Top Us Leaderboard in installed wind capacity, performance" [14]
This article reviews top utilized wind turbine companies used in the United States. The largest two companies are General Electric and Vestas, followed up by Siemens Gamesa. The team used this source to guide on turbine selection, having had no previous experience with turbines.

"Haliade 150-6MW offshore wind turbine" [15]
This manufacturer website provides many specifications for one of the General Electric offshore turbine designs, including hub height, power rating, rotor specifications, and tower type. This source was used to compare to other potential selections of turbine.

"Offshore wind turbines" [16]
This Vestas manufacturer website provides data about Vestas offshore wind turbine designs, including installed locations, installed power capacity, and some of the specific turbine designs. This source was used to locate suitable Vestas turbines for concept generation.

"Scaling up the use of offshore wind turbines" [17]
This manufacturer website provides data about Siemens Gamesa offshore wind turbines, similar to source [16]. Like the Vestas site, it provides installed power capacity for various countries, as well as various turbines that have been designed for offshore. This source was used to locate suitable Siemens Gamesa Turbines for concept generation.

"Port and Shipyard Requirements for the Installation of Floating Wind Turbines" [18]
This source explains different types of ports and shipyards and related terms. It provides details on space and machinery needed for floating wind turbines. This source is utilized to ensure that when selecting a turbine, the team also considers assembly needs for it.

“Vestas V236-15.0 MW introduced” [19]
This article briefly reviews a new design for an offshore Vestas turbine, with prediction of cost. This source is used to estimate the costs of the selected turbines for comparison. While not fully accurate, it gives the team an expectation.

3.2.3 Anchor Selection – David Lemar-Perez

There are two types of anchor foundations, gravity based and floating. For the project, the team is focusing on offshore base foundations that would focus on the most efficient locations on the great lakes without harming wildlife and the environment. To compensate for the harsh characteristics from temperature and icing, the best foundation that would mitigate this is either Tension-Leg Platform or the Hybrid. These two platforms are ideal for eliminating deep water currents which add force to the structure and movement which is undesirable. Ice can form easily but TLP’s are known to have also withstand the amount of icing and capsizing force, the amount of tension by mooring ropes have been also able to withstand icing. The material used is buoyancy dependent that takes up less weight overall for efficiency.

Reference 20 is where it demonstrates what anchor is best suited for lakes related to lake Michigan or Lake Superior.

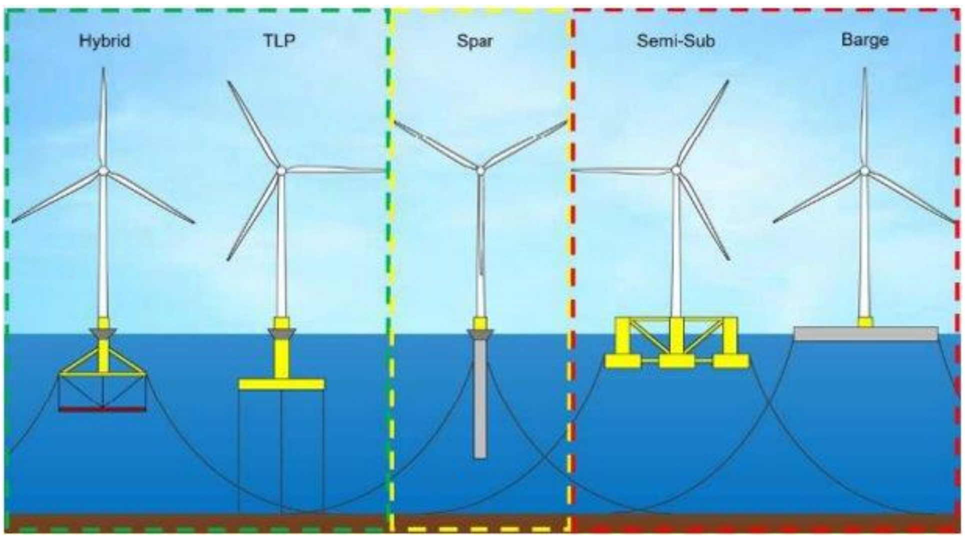


Figure 3.2.3.1: Different types of anchor designs

The type of style for the anchor is like a lattice floating hybrid or a floating structure with mooring ropes attached to it like a Tension Leg Platform.

Article 21 talks about “Acteon,” a program that can illustrate geological and soil properties in evaluating different types of anchors that can be simulated within these conditions. The program specifically focuses more on floating wind testing bases. In the end it also verifies the cost and the availability of certain materials.

Article 22 is focused more on specific data like micro bathymetry for Preliminary design of anchors focused on offshore wind turbines. Using data like analyzing how much force is being generated from structures to collecting soil samples in a region and finding tension in mooring lines. This resource is useful in using graphs that best represent in calculating efficient performance numbers once an anchor style has been selected and the location too.

Article 23 is looking into recent offshore wind turbines that are currently working around the world as well as a brief description in which offshore wind turbine anchors are being selected for future use. It touches on the subject of whether certain regions will accept certain buildings near cities or villages due to local agreements and environmental concerns.

Article 24 has a set of info regarding wind turbines but specifically it touches on the subject on anchors on how each factor is crucial in how anchors are affected the most. The design quality, fatigue due to corrosion, overload, manufacturing defects, installation, and out of plane bending, etc. These factors are also addressed due to the reliability of how anchors are also a big part of the whole turbine design.

3.3 Mathematical Modeling

3.3.1 Site Selection – Alexander Longoria

In order to justify the selection of the Great Lakes, the team utilized the equations described in reference 4, *Investment cost and view damage cost of siting an offshore wind farm: A spatial analysis of Lake Michigan,* and coded them into MATLAB to obtain the results.

Equation 1 solves for Willingness to Pay; this variable tells the team how much a resident is willing to pay (WTP) as an additional cost or willing to accept (WTA) as a discount towards their month electric bill based on the specific distance the offshore wind farm is from the shoreline. The equation is listed below,

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

As seen in the equation, the only input to the function is $D_{farmtoshore}$. This variable is used to denote the offshore wind farm distance from the shoreline. The "–WTA" represents the instance in which the residents will receive a discount. After this equation is coded in MATLAB, the team will conclude that 27.47 miles is the ideal distance for keeping the WTP and WTA the lowest. This can be seen in the graph below.

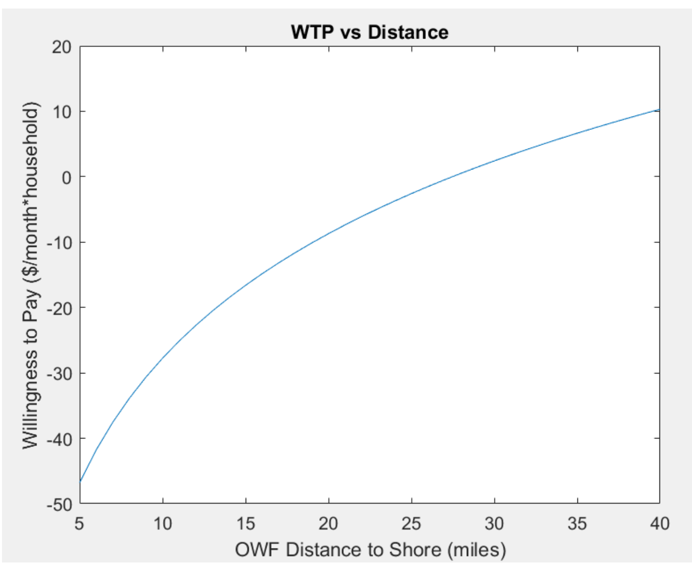


Figure 3.3.1.1: Willingness to Pay vs Farm Distance

The next equation that was derived from reference 4 solves for the Annual View Damage Cost (VDC). VDC is defined as the cost to residents from the visual disamenity of the offshore wind farm within the viewshed of the households. Equation 2 is listed below.

$$Annual\, VDC\left[\frac{US\, dollar}{year}\right] = WTA \cdot 12\, months \cdot h \qquad [2]$$

Where "h" is the total number of households within viewshed of the farm. When using this equation for analysis of both Great Lakes, the team can estimate that there are 439 households in Lake Michigan and 351 households in Lake Superior. This equation is directly proportional to equation 1, meaning that the distance between the farm and shoreline are stiff influences the results. This can be seen in the graph below.

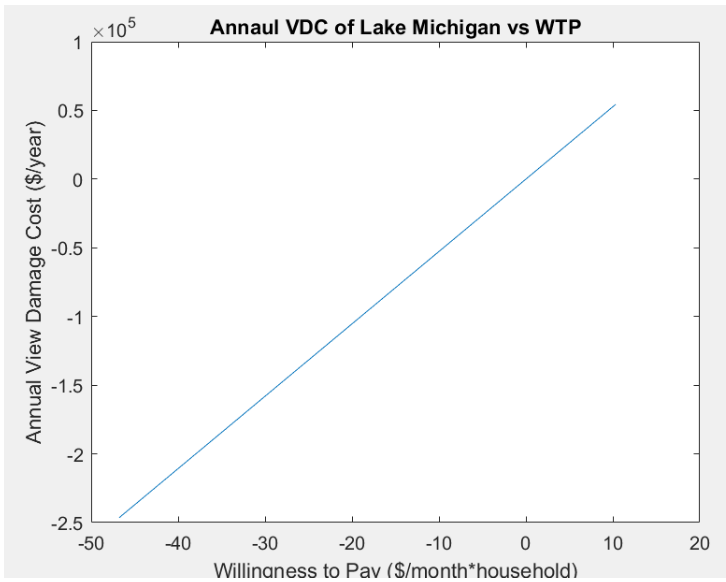


Figure 3.3.1.2: Annual View Damage Cost of Lake Michigan vs Willingness to Pay

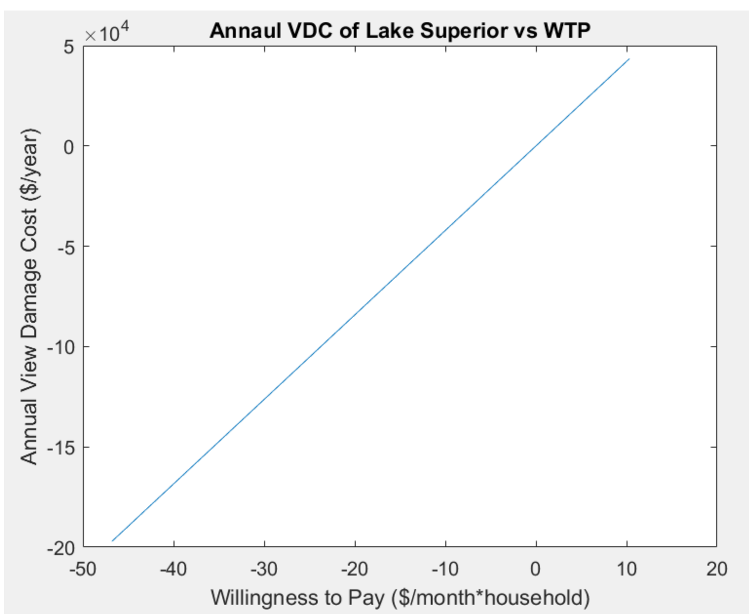


Figure 3.3.1.3: Annual View Damage Cost of Lake Superior vs Willingness to Pay

The last equation will tell the team the Net Present Value VDC. This will tell the team the present value of the VDC with consideration of an estimated discount rate of 3% per the reference. This finding will be evaluated over the 20-year life span of the farm (n).

$$Net\ Present\ Value\ VDC\ [US\ dollar] = \frac{Annual\ VDC}{r} \cdot \left(1 - \frac{1}{(1+r)^n}\right) \qquad [3]$$

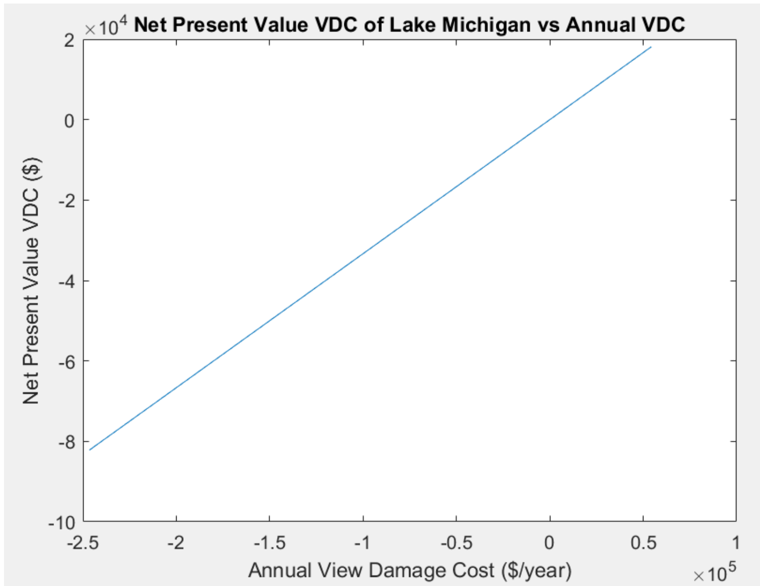


Figure 3.3.1.4: Net Present Value VDC of Lake Michigan vs Annual VDC

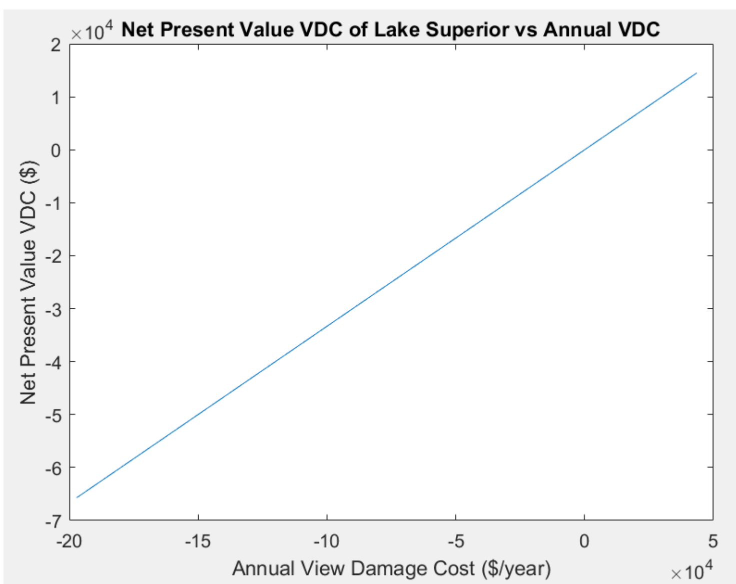


Figure 3.3.1.5: Net Present Value VDC of Lake Michigan vs Annual VDC

Part of the team's end goal is to minimize the Levelized Cost of Electricity (LCOE) and the reference provides the appropriate equation to solve for it (equation 4). However, at the time of writing this report the team does not have enough data about the annual energy production based of the turbine the team decides. Therefore, the team cannot generate a reasonable value.

$$View\ Damage\ LCOE\left[\frac{US\ dollar}{MWh}\right] = \frac{Net\ \Pr esent\ Vaule\ VDC}{Annual\ Energy\ \Pr oduction\ (net)\cdot n} \qquad [4]$$

3.3.2 Turbine Selection – Samantha Russell

In order to justify turbine selection, some analysis is required for farm power output potential, turbine spacing, and turbine cost. The following equations are rudimentary and used for the purpose of narrowing choices and team understanding of the topic.

The first equation is guided by [13]. From the parameters there, a general special analysis was done with eight diameter spacings between turbines in the wind direction, and five diameter spacings between turbines opposite the wind direction. This has not been optimized, as each turbine may be placed closed or further from each other based upon airfoil design and wake analysis. This gives an analysis of the possible air turbines in a leasing spot. An assumption of leasing area of 100 square kilometers was used.

$$\#\ Turbines = \frac{10km}{9*D} * \frac{10km}{6*D} \qquad [5]$$

Further, to compare the possible power output for the same area between the different turbines, the number of turbines was multiplied by the rated power output of the turbine.

$$Plant\ output\ power\ =\ Turbine\ \cdot\ Rated\ Power \qquad [6]$$

These calculations, while simplistic, help to narrow down to three potential turbine selections. More in depth analysis will be done with the selected turbines to narrow down to a final choice using Furow, a wind plant analysis tool suggested by NREL and The Department of Energy. Figure 3.3.2.1 below displays an example of how furrow will help to visualize power output.

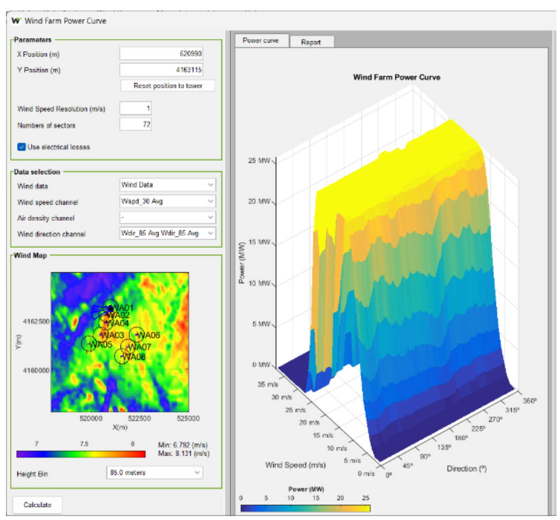


Figure 3.3.2.1: Furow Power Analysis

3.3.3 Anchor Selection – David Lemar-Perez

Article 23 represents an anchor that was tested in Germany that focused on creating cost efficient floating platforms, that was reliable in lightweight, and size compared to spars and semi-submersibles. Using computer aided engineering like “aero-hydro-servo-elastic coupled simulations” help managed scale a model like in a real life windshore turbine location. Testing from decay to mooring rope tension attached to the platform helps test many factors that could simulate real time effects like on the great lakes. The test that was conducted was a similar build like a TLP but with some modifications that added lattice designs with 8mm stainless steel threaded rods and other parts made with polyoxymethylene material for lightweight and durability; also coated with epoxy for less drag on water. Mooring ropes where attached calculations needed to be accounted for stability if such wind or wave conditions hit and did not make the platform stable. Mooring ropes are attached where OpenFAST computer program calculates the tension in the ropes in which it told how much strength is needed to not have it capsize or tear apart. The equation below is taking the Yield strength and having a certain tolerance boundary for efficiency. Then calculating the ropes extensional stiffness of within that range. The C target equation is for the correct axial stiffness for the coiled springs along with attached steel ropes. Most of this is 1:100 scaled for fitting a real time simulation which performed better than most platforms which would not be suitable for 60m or more depth offshore locations.

$$130 \times 10^3\ \mathrm{N/mm^2} \leq E \leq 150 \times 10^3\ \mathrm{N/mm^2} \tag{7}$$

$$408,400\ \mathrm{N} \leq EA \leq 471,239\ \mathrm{N} \tag{8}$$

$$c_{target} = \frac{EA \cdot \frac{1}{\lambda^3}}{l_0 \cdot \frac{1}{\lambda^1}} = \frac{2146,000,000\ \mathrm{N} \times \frac{1}{50^3}}{168,421\ \mathrm{mm} \times \frac{1}{50}} = 5.097\ \mathrm{N/mm} \tag{9}$$

4 Design Concepts

4.1 Functional Decomposition

The simplified overall purpose of the hypothetical wind power plant is to transfer energy from the wind to the local communities and individual houses. This explanation takes it a bit further than the team's design, as the project development team does not need to distribute the energy to individual utilities, just design the connection to the electrical grid with consideration of local energy needs. To this end, the CWC24 Project Development Competition's functional decomposition provides a visual of tracking the energy from the wind to the houses. This can be found below in Figure 4.1.1.

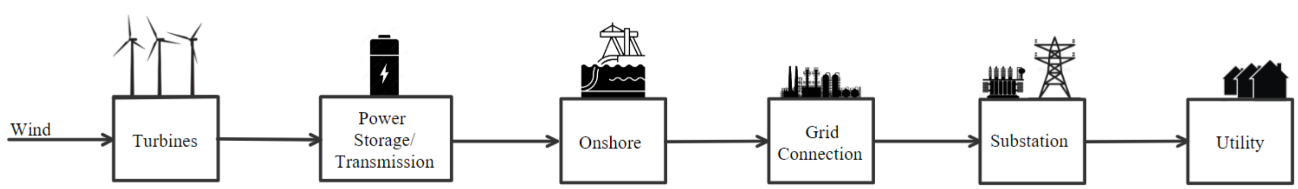


Figure 4.1.1: CWC24 Project Development Functional Decomposition

Amongst these simple breakdowns, the team must especially consider connections. Transmitting the energy onshore can often be an expensive process due to distance and cable requirements. When connecting to the electrical grid, care must be given to local and federal laws, as well as how the plant's provided energy will affect the grid's power supply and needs. Throughout the process, the team needs to consider how each connection point may best be made so as to not cause harm to any stakeholders such as the environment, local Native lands and people, and utilities, among others. The functional decomposition will help the team to recognize all the potential hazards, stress points, and the over-arching goal of the hypothetical wind farm.

4.2 Concept Generation

4.2.1 Site Selection – Alexander Longoria

Given that the DOE preassigned each team to analysis Lake Michigan and Lake Superior, there isn't much traditional concept generation that can be made. Therefore, the team's goal is to consider all the top-level and sub-level characteristics of each Great Lake and compare them receptively.

The initial evaluation of the Great Lake would be to consider some of the big picture pros and cons. The table below lists those attributes.

Lake Michigan		Lake Superior	
			
Pros	Cons	Pros	Cons
Max depth of 925 ft	Sixth largest freshwater lake in the world by surface area	Largest freshwater lake in the world by surface area	Max depth of 1,332 ft
Northern part is forest	136 species of fish	80 species of fish	1/4 shared between Canada
	300 miles long	350 miles long	Commerical fishing
	22,230 square miles	31,820 square miles	
	Population: 12 million	Population: 425,548 USA 181,573 Canada	

Figure 4.2.1.1: Pros and cons of the Great Lakes

The next step would be to consider some of the more technical concepts to help drive the team to come to a final decision about the location of the offshore wind farm. For example, the team will consider the mean wind speed at different hub heights, optimum LCOE locations, points of interconnection, power plants and infrastructure capacity, distance from major cities, and bathymetry data.

4.2.2 Turbine Selection – Samantha Russell

From the top three production companies in the United States for Wind Turbines, ten possible turbines were selected. Of these, several were eliminated right away for not being rated for offshore performance. These turbines were initially picked as they were a preloaded turbine possible for selection in Furow.

Two Vestas, one General Electric, and three Siemens Gamesa turbines were analyzed. Initial pros and cons of each turbine are listed in Figure 4.2.2.1 below. Each turbine is further analyzed in the next sections.

V236-15		V174-9.5		GE150-6	
pros	cons	pros	cons	pros	cons
largest power rating	not commercially manufactured till 2024	average cut in and cut out speed	mid-high initial cost	lowest port infrastucture needs	low individual power rating
above average cutout speed	high needs port infrastructure	highest rated power output for 10kmx10km area		average cut in and cut out speed	

SG132-5		SG200-11		SG222-15	
pros	cons	pros	cons	pros	cons
lowest port infrastucture needs	differing view on offshore capability	large swept area and rated power	data for cut in and cut out speed not made easily available	second highest rated power output for 10kmx10km area	high needs port infrastructure
lowest relative cost	low individual power rating				data for cut in and cut out speed not made easily available
high rated power output for 10kmx10km area					

Figure 4.2.2.1: Pros and Cons of Turbine Choices

4.2.3 Anchor Selection – David Lemar-Perez

Onshore foundations are not the scope of this project but have a good idea implementation towards offshore projects. If a certain location in the great lakes is chosen where there is not much depth, then structures with this design should be considered. Gravity-Base foundations are the best since they require only flat ground which in time some soil can be disrupted due to current and can offset the turbine. Tripods are the second-best option since they require some excavating depth to place the foundation, but the soil has to be dissolved more and not disrupted or it could affect stability through time. Mono bucket is the third option since it is like Spar but with a strong excavating bucket base which supports most forces, the only problem is deep water currents which can add forces within the bucket and the outside of the bucket to move more through time since the walls of the bucket add some slippage. Monopile is not really reliable since it's thinner and requires more excavating to insert in the soil and can also sink through time. Jacket is the worst by too much material and more joints involved which can affect stability through time, plus it can collect rust easily but hey it can also build a coral reef if enough fish are around because of the electrons generated by ocean salt connected to the river.

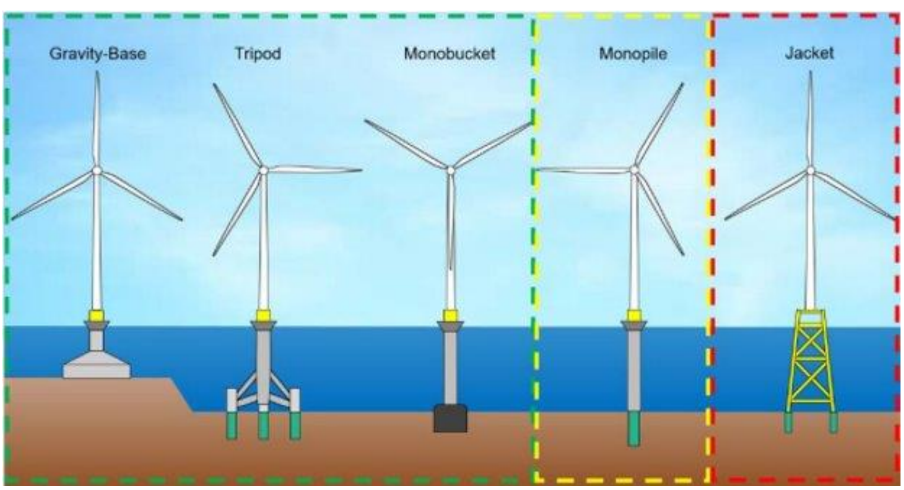


Figure 4.2.3.1: Different types of anchor designs

Offshore Wind turbines are demonstrated below ranking from best to worst on color description left to right. Hybrids are specific designs like mods that have different structural styles like TLP's that are mor focused on attachments with mooring cables. TLP's are a standard design option for offshore purposes. Both are the best option since they don't disrupt soil, have icing problems due to material and insulation wrap around structure, and is not affected by deep water currents. Hybrids can also be quite expensive due to design modding. Spars are the second-best option since they are known to be very still and easy to install by using a hammer and cutting the top of it later. Very little material is incorporated but can gather some rust through time. The last two options are the worst since they have icing problems that are collected in the platform and add weight that could tip the wind turbine. Durable but too much material like concrete.

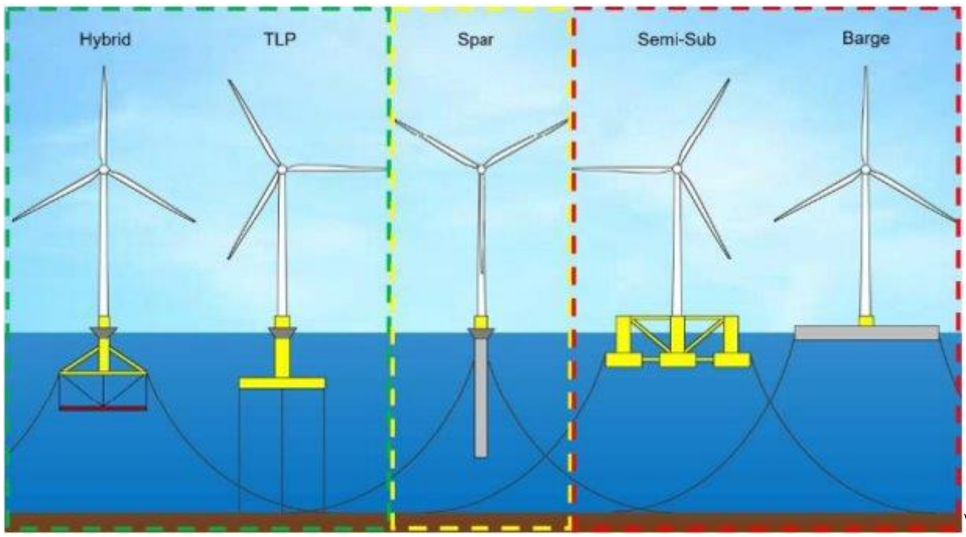


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Figure 4.2.3.2: Different types of anchor designs

4.3 Selection Criteria - All

4.3.1 Siting Selection – Alexander Longoria

This section of the report will go into more depth about the technical concepts briefly described in section 4.2.1.

Wind speed at different hub heights is one of the key driven data that affects the whole system. For an area as big as the Great Lake, the wind speeds at different elevations vary due to the bordering tree lines and residents. Therefore, the team can see which areas would benefit from different hubs height. The figure below shows the wind speed data at a hub height of 140m.

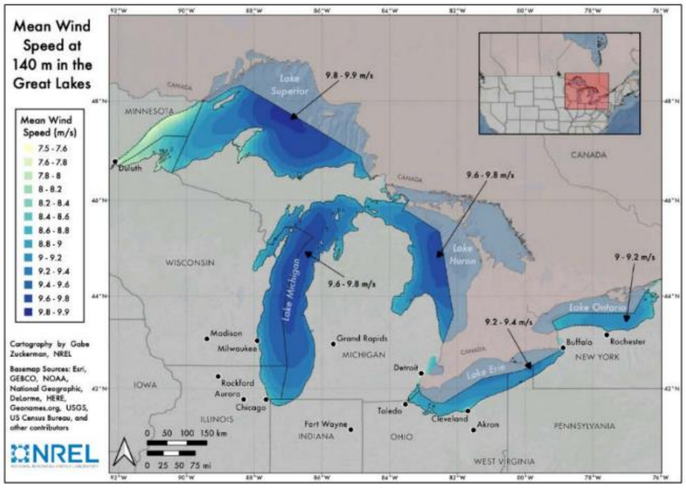

Figure 4.3.1.1: Mean Wind Speeds at 140m

Finding the optimum LCOE location is an important factor to consider because this relates to the amount of money the resident is paying per Mega Watt Hour (MWh). The team strives to keep the costs low for each household while trying to make a profit. As a result, the distance from the shoreline can be estimated using the map below.

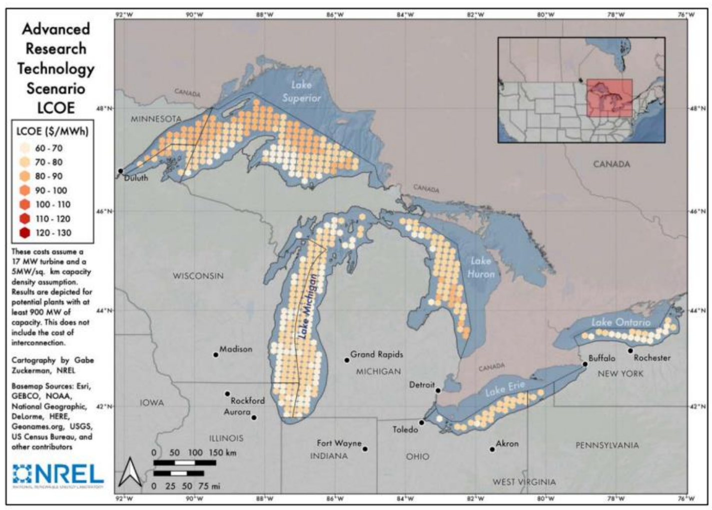

Figure 4.3.1.2: Estimated LCOE values based on location

Points of interconnection is a term used to describe the substation and power plant within a given location. As the team aims to produce an estimated 150 MW, finding existing points of interconnection is important. The ideal location would consist of minimizing the distance from the farm to the on-land substation and to major cities, finding a power plant that has similar transmission capacity and is retiring by 2030.

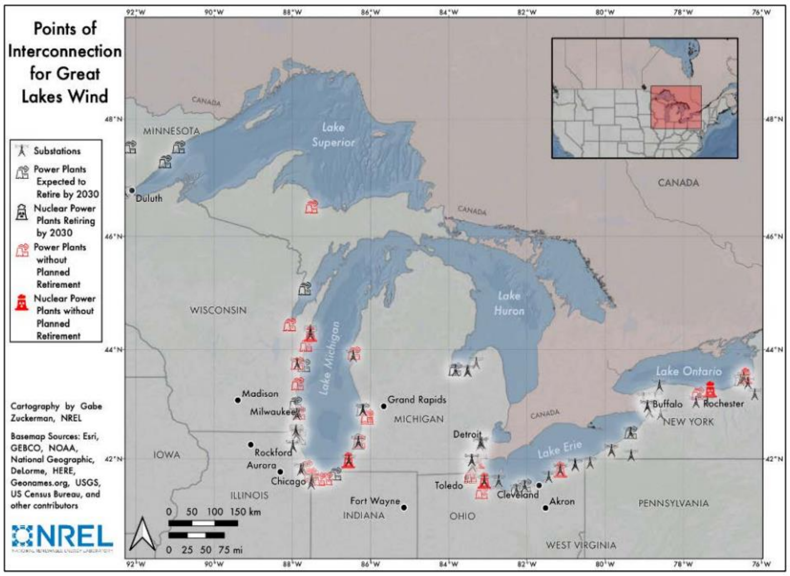

Figure 4.3.1.3: Points of interconnection

The last top-level consideration is the bathymetry data. This information will tell the team the water depth measurement at different locations within the lakes. This data will aid in lowering the total cost of the farm by telling the team where a fixed or floating anchor design is needed. The team will use the map below to make that decision.

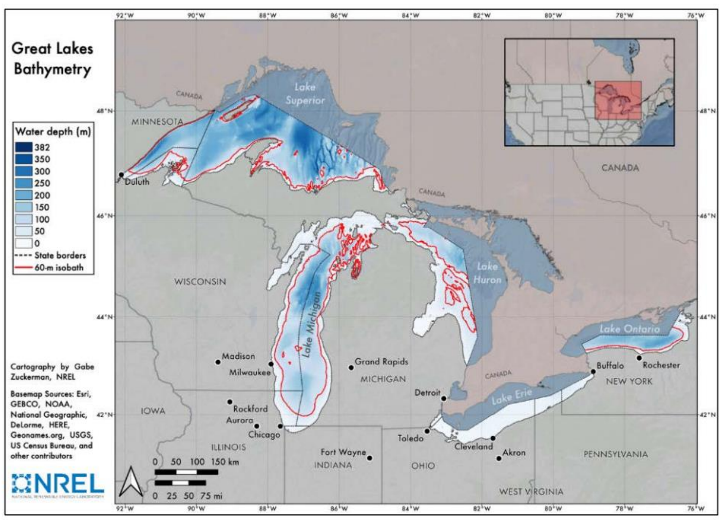

Figure 4.3.1.4: Bathymetry data

4.3.2 Turbine – Samantha Russell

Criteria used for analyzing turbines include rotor diameter, cut in and cut out speed, power rating, max possible turbines per 100 square kilometers, rater power output for 100 square kilometers, turbine cost, and port infrastructure requirements. These criteria were developed as simple and effective ways to compare the turbine selections, and ways of meeting engineering requirements from the House of Quality as they relate to turbines. The criteria were rated from the House of Quality and applicable engineering requirements, and their ratings, therein. Criteria that fell under an engineering requirement that was rated as more important received higher ratings based on the percentage importance found in the House of Quality.

4.3.3 Anchor Selection – David Lemar-Perez

The criteria used for anchors is data collected from factors that affected the failure of the anchor. These factors are fatigue being the most caused issue, installation, mechanical accuracy, corrosion, design, and overload. From these probability factors, they were tested among different designs and seemed to single out the best benefactor of the design. Reference 27 has a pie chart that best describes this analysis of how anchors are affected mostly by these definitions. These are the engineering requirements we must meet to have the best quality build in our project.

4.4 Concept Selection

4.4.1 Site Selection – Alexander Longoria

The traditional method of 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 electing to neglect the Pugh chart just move forward with a decision matrix.

Now that all the relevant resources, equations, and figures are determined, the team will into Lake Michigan and Lake Superior into a decision matrix based on engineering and customer requirements stated in the QFD. A weight is assigned to each criterion and scored based on their relevance. A weighted score is then added based on the score and this will tell the team which location to pursue. The figure below states all the criteria that analyzed with its respective scores.

		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

Figure 4.4.1.1: Site Selection Decision Matrix

4.4.2 Turbine Selection – Samantha Russell

The six turbine selections were analyzed via a decision matrix. Before analyzing them, however, each criterion in section 4.3.2 was weighted with importance. To do this, the team utilized the engineering requirements from the QFD that were relatable to turbine analysis. This included the area of the leasing block, farm power output, levelized cost of energy, wind data, and port infrastructure. Then, using the importance percentage weight from the House of Quality for each related engineering requirement, each turbine criteria within an engineering requirement was given a point value, such that the sum of the points was equal to the importance of that engineering requirement. For example, levelized cost of energy, rated 9% in the House of Quality, was made up of the criteria rated power output per area and turbine cost, each of which were given points that summed to nine, such as five and four. These points correspond to a weighting percentage to ensure that more important aspects of the turbine selection are represented as such in the selection process.

Then, a scale of one to ten was created for each criterion. This scale is shown in Table 4.4.2.1 below. More favorable outcomes were rated higher.

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 4.4.2.1: Turbine Selection Criterion Scoring

Finally, each turbine was scored based on this scoring rubric in a decision matrix, visible in Table 4.4.2.2 below. The top three turbines were selected to continue in the down-selection process. These turbines are the Vestas V174-9.5, General Electric GE150-6, and Siemens Gamesa SG132-5. Each of these turbines will undergo much more rigorous analysis and modeling in Furow with full farm data. The team chose to model the top three turbines so as to have each team member model one farm. An enlarged view of this table is available in Appendix A.

		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 4.4.2.2: Turbine Selection Decision Matrix

4.4.3 Anchor Selection – David Lemar-Perez

The anchor selection was based off numbers ranking from 1 through 10, that being ten the best and 1 the worst. Then rating each one from factors that were crucial in technicality, cost, safety, environmental impact, installation, port accessibility, weight, and modeling. TLP came out on top because of standard issue over hybrid but hybrid is the most efficient in build, but cost could be a problem because of design quality.

		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 4.4.3.1: Anchor Selection Decision Matrix

5 CONCLUSIONS

Per the DOE, the WindJax Project Development team is tasked to research wind resource data, transmission infrastructure, and environmental factors to create a site plan and financial analysis for a hypothetical offshore wind farm based on Lake Michigan and Lake Superior. The team decided to slip into 3 different sub sections: Site Selection, Turbine Selection, and Anchor Selection.

The conclusion of each sub section suggest that the team has decided to move forward with a TLP anchor design based in Lake Michigan. The turbine is the heart of this offshore wind farm and at this point in time the team has not yet decided on a final model, rather, the team has elected 3 models (Vestas V174-9.5, General Electric GE150-6, and Siemens Gamesa SG132-5) to endure further evolutions in Furrow.

The content of this report stated all the relevate resources, appropriate equations, concept generation, and concept selection. This report was constructed in a way to show the client the progress of NAU CWC24 Project Development team over the course of a few months. The next step for the team is to continue to research the final selections and move forward with a modeled prototype that encompasses all the conclusions and design consideration stated in this report.

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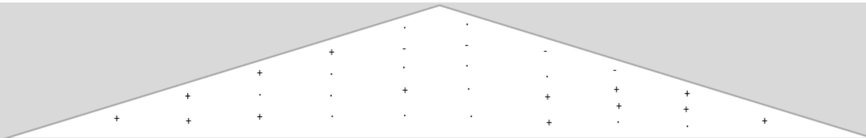
7 APPENDICES

7.1 Appendix A: Larger Decision Matrices and Pugh Charts



1: low, 5: high	Desired direction of improvement (↑,0,↓)	↑	↓	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
Customer importance rating (for full competion points)	Engineering Requirements (How's) → Customer Requirements - (What's) ↓	Area of Leasing Block (km^2)	Levelized Cost of Energy ($/kWhr)	Farm Power Output (150 MW)	Wind Data (85-100m 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, connection type)	Community Usage Data (<100 people in area monthly)
5	20 year lifespan	0	0	0	5	5	9	5	5	0	0	0	1
5	Siting Selection	9	0	0	9	9	9	9	5	9	9	5	9
5	Technology Selection (Turbine, Anchor, Energy Transmission)	5	9	9	9	9	5	9	5	5	0	5	0
5	Development and Technical Integration Plans	9	5	5	1	0	0	9	9	5	9	9	5
5	One other generation, storage, or end-use technology	5	5	5	0	9	5	5	5	5	1	5	1
4	Harm mitigation strategies for affected ecosystems	9	0	0	5	5	1	0	5	9	5	0	1
3	Local Community Impact	1	1	5	0	1	1	5	5	1	5	5	9
5	Financing Plan - annual costs, market incentives, etc	5	9	9	5	0	0	5	1	0	1	1	1
4	Cost of Energy and cash flow analysis	1	9	5	5	0	0	5	5	0	0	5	0
3	Annual Energy Production	5	1	9	9	1	5	0	0	1	0	0	0
5	Bid for potential Lease Block	9	9	5	5	0	0	5	5	0	0	1	0
	Technical importance score	228	179	155	165	138	122	225	205	134	135	140	116
	Importance %	12%	9%	8%	8%	7%	6%	12%	11%	7%	7%	7%	6%
	Priorities rank	**1**	**4**	**6**	**4**	**6**	**8**	**1**	**2**	**5**	**3**	**7**	**12**

Figure 2.3.2: House of Quality

7.2 Appendix B: Bibliography – Other Relevant Literature

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