Preliminary Site Design Milestone

2024 Collegiate Wind Competition

April 18, 2024

California Polytechnic State University, San Luis Obispo

Team Lead:

Trevor Ortega – tdortega@calpoly.edu

Team Members:

Kyle Richardson – kqrichar@calpoly.edu

Timothy Reyna – treyna@calpoly.edu

Danny Ho – dho34@calpoly.edu

Club Advisor:

Andrew Kean – akean@calpoly.edu

1 Summary

The California Polytechnic Wind Power Club has selected a site located in the Great Lakes and developed a proposal for a wind farm with a rated power of 124 MW for the Project Development Contest of the 2024 Collegiate Wind Competition. Based on analysis of environmental and economic concerns, the site is located 11 miles South-East of Milwaukee along the western shore of Lake Michigan and consists of 36 Vestas V136-3.45 with a fixed bottom foundation. The power will be sold at an initial PPA price of $110/MWh and we expect an average annual production of 535,000 MWh resulting in a net capacity factor of 49%. The project will be financed by the issuing of Green Bonds. Financial and economic analysis was performed with a custom Excel program.

2 Site Details

2.1 Site Selection

Selecting an appropriate site requires analysis of various factors which must be weighed against each other before a location can be chosen. Consideration was given to wind speed, water depth, distance to shore, transmission access, ice cover, lakebed geotechnical properties, environmentally protected areas, bird and bat behavior, critical fish habitats, population centers, transportation access, shipping lanes, military zones, flight paths, and lake use. Based on these criteria, a down-selection was performed to 5 areas, as shown in Figure 1, which were then considered in greater detail for ancillary benefits such as local community impacts, co-generation potential, and port access. The process of performing this down selection was done in stages to make research more efficient.

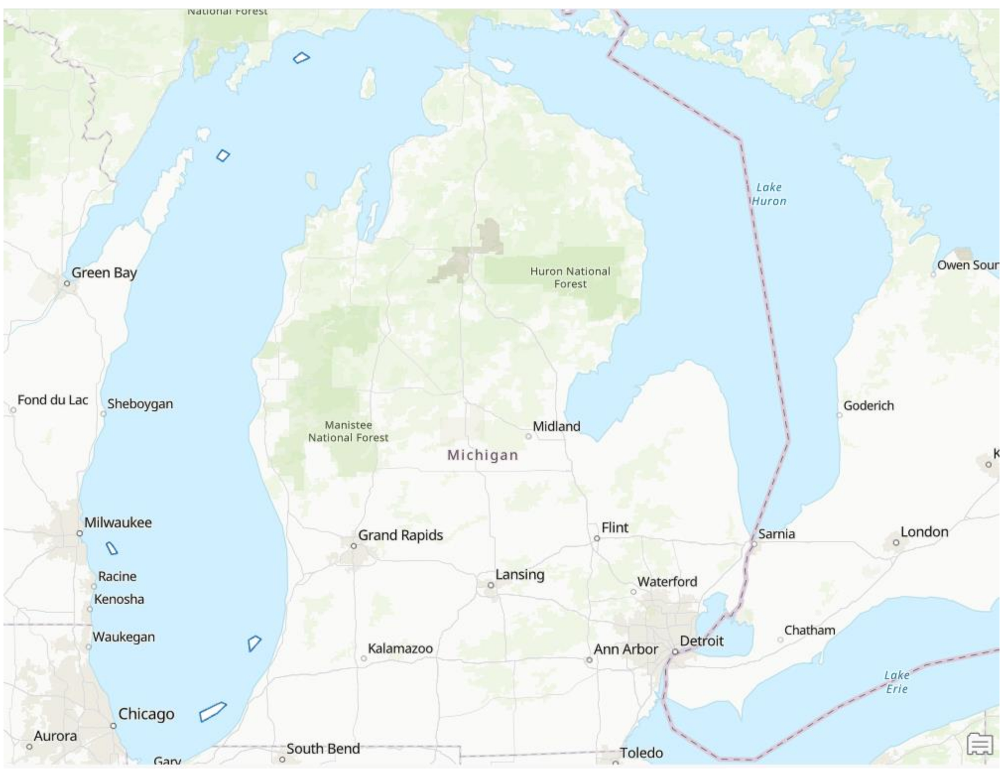


Figure 1. Map of Lake Michigan showing our final 5 possible locations as white areas outlined in blue. Two are located at the northern end of Lake Michigan, and 3 are located in the southern portion of the lake.

2.1.1 Initial Evaluation

The first stage was consideration of general trends in some of the most important criteria, such as wind resource and bathymetric data. Wind speeds showed a range from 5.5m/s to 9.5m/s in Lake Superior and 7m/s to 9.4m/s in Lake Michigan as shown in Figure 2 [1]. The lowest speeds are seen close to shore, with higher speeds near the center of both lakes. Lake Michigan and Eastern Lake Superior both show a sharp increase to around 8m/s within a few miles of the coast, followed by a much more gradual rise in speeds moving towards the center of the lake, while the Western Half of Lake Superior has lower speeds overall and a more gradual rise from the edges to the center. Based on these speeds, the majority of both lakes are classified as having IEC Class II medium winds [2]. Because the lakes demonstrate relatively even wind speeds, factors other than wind speed will have a larger impact on the competitiveness of a given location.

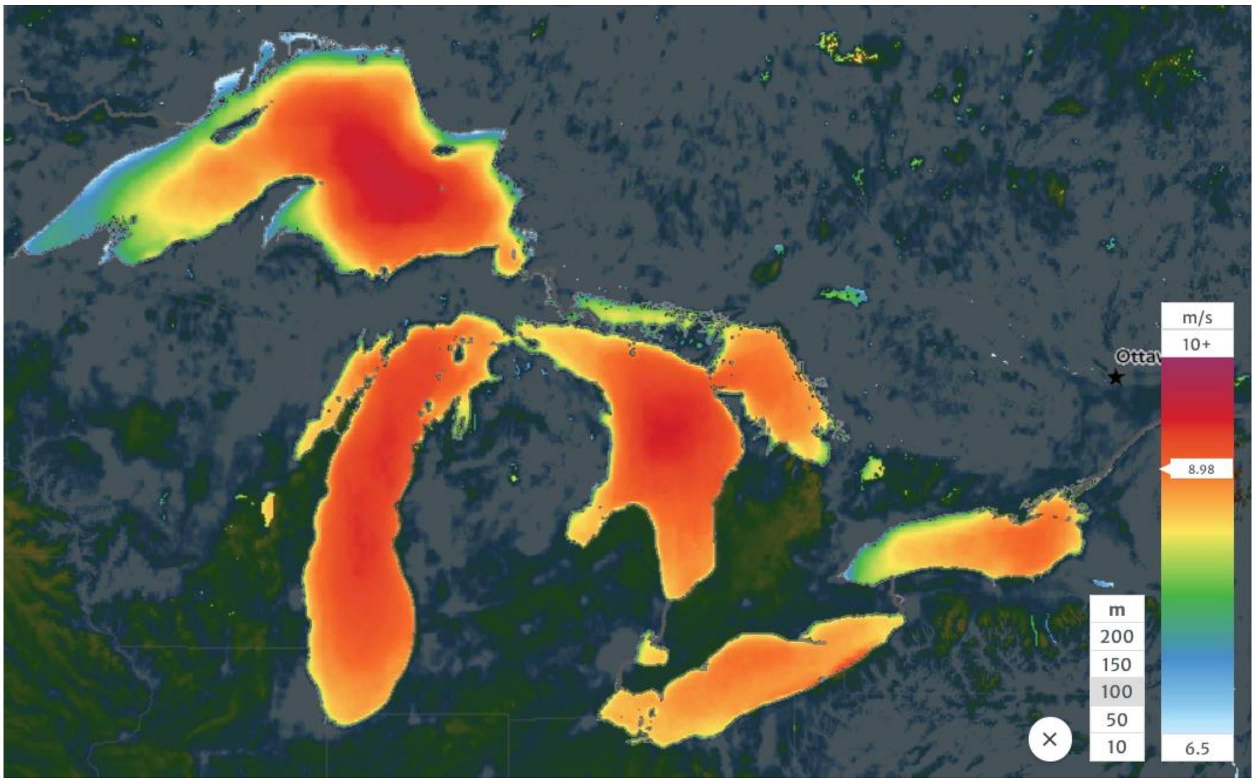


Figure 2. Map of wind speed data with lakes highlighted showing wind speeds varying from 6.5m/s to 10m/s. This information was used to make preliminary decisions early in the development process.

2.1.2 Lake Depth Consideration

The lake depth is a critical factor because of the impact it has on what foundations can be used. Fixed bottom foundations have a more proven track record with 59,000 MW of installed fixed foundation capacity compared to just 123 MW of floating capacity [3]. Generally, a floating foundation is required for depths greater than 60m, while fixed platforms are feasible if under 60m [4]. Bathymetric data shows more complex topography than the wind speed data; however, a few key trends were identified [5]. Lake Michigan has two main basins, with the northern basin being the deeper of the two. There are large shallow regions less than 30m deep at the northern end of Lake Michigan near the Mackinac Straight and in the Green Bay. The southern end of Lake Michigan also has a gentler slope, which presents significant areas with a depth less than 60 m. Lake Superior is generally deeper, with a much steeper gradient, presenting fewer areas less than 60 m deep.

2.1.3 Migratory Areas and Sensitive areas

The Great Lakes serve as a migratory corridor for birds and bats, however the majority remain within 6 miles of shore, so by adding a further 4-mile buffer beyond this region we will reduce the effect of our farm on the ecosystem. A buffer zone placing us at least 10 miles offshore will also help minimize viewshed impact [6]. Areas protected from development and managed to maintain biodiversity were excluded based on data from the USGS National GAP Analysis Program [7]. Reefs and fish spawning zones were also marked as these locations are more sensitive to ecosystem disruption [8]. The Great Lakes shipping industry is a key economic driver, so the entirety of Lake Michigan sees heavy traffic, but designated shipping lanes were identified and avoided, as well as other areas of particularly heavy traffic [9]. Because of the historically heavy traffic within the region, there are a large number of shipwrecks, which are also protected areas and must be avoided [10].

2.1.4 ArcGIS Downselect

Once protected areas had been identified and marked as ineligible for development, an ArcGIS map was produced which combined layers and highlighted areas that met all our site criteria. Within these areas we identified 5 specific site locations which were large enough for a viable farm. These locations could then be compared directly against each other in terms of average wind speed, access to transmission, and potential for cogeneration. These locations are shown in Figure 1. The two locations in Northern Lake Michigan had higher wind speeds at 9. m/s while the 3 locations in the south were closer to 8.8 m/s, around 10% less in terms of energy potential. The three southern locations had significantly better access to infrastructure both in terms of ports and transmission capabilities [11]. The remaining significant difference between the locations is that those on the west side of the lake have a subsurface classified as hard, while those to the east are muddy [12]. Based on the depth all sites would require jacket or tripod-style foundations, but harder sites would require piles while the muddy sites would benefit from caisson-style foundations. Of the three southern locations, the site near Milwaukee has the best transmission access and is at least equal in all other characteristics. Therefore, it was selected as our final site location.

2.2 Site Characteristics

As stated in the introduction of the report, the wind farm site has been placed on the western shore of Lake Michigan. Wind speeds at 150 m height average around 9.37 m/s, which is the upper end of wind speeds in the entire Great Lakes region. Since the site is not too far from the shore, the water depth of the site is between 45-60 meters, meaning that fixed foundations are feasible for the turbines used in the wind farm. The roughness length of the site is very low, so there is little to no interference from surface objects slowing down the wind speed in the selected site. The soil composition of the site consists primarily of alfisols, spodosols, and inceptisols. Another possible component of the soil is heavy metals and industrial chemicals from the 1960s and 1970s before environmental regulations were enacted. These toxic contaminants have settled into lakebed sediments and could be disturbed during wind farm installation [13]. Our location does not have a record of heavy metal contamination, but soil samples should be taken as a precautionary measure.

2.2.1 Icing Concerns

An additional environmental concern unique to development in this region is the presence of freshwater ice. Significant work is needed to fully characterize ice presence on the lakes and determine its impact on turbine structures. All areas of the Great Lakes experience surface ice at least occasionally so there is no way to avoid this issue completely. Generally, ice concentrations decline when moving south and towards the center of the lakes. Therefore, the selected site in the Southwest of Lake Michigan has the lowest ice levels of the sites considered with a typical concentration of only 5% [14]. Lake Michigan also sees significant wave height fluctuations depending on the season; wave heights can reach 7 meters during Fall but are 0.5 meters or less in Spring and Summer [15].

2.2.2 Human Activity

Human activities in the region consist of active fisheries, tourism activities hosted by large cities such as Chicago, and professional fishing activities. Parts of Lake Michigan in Chicago and Indiana are very popular; it is estimated that 60 million people use the Chicago lakefront each year for various purposes. A recent study suggests the Great Lakes are a key economic driver, being directly associated with over 1.3 million jobs and producing $82 billion in wages [16].

2.2.3 Endangered Species

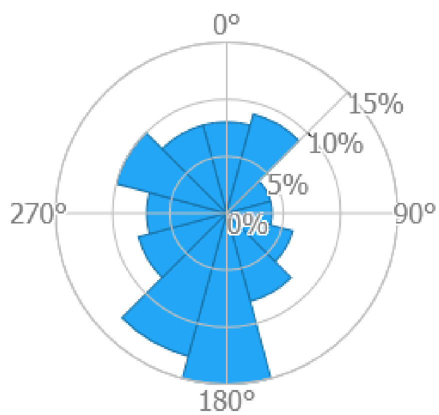
Within Lake Michigan, there are several endangered or threatened species, such as the Northern Long Eared Bat, the Indiana Bat, and the piping plover [17]. We will follow relevant federal and state guidelines regarding the safe operation of a wind farm in areas near these species. The Northern Long Eared Bat was reclassified as endangered in 2022, and guidelines were published by the U.S. Fish and Wildlife Service for the operation of wind farms within the bats' range. These guidelines only apply to land-based wind farms but can still be followed until guidelines for offshore turbines have been established. As the farm is offshore it already meets all buffer zone requirements. Other requirements include feathering the blades beneath 5 m/s during the migration period and specified mortality monitoring and reporting [18]. The Indiana Bat is also listed as endangered and potentially present in the region, so a similar set of guidelines must be followed [19]. The endangered piping plover has nesting sites on shore; however, our distance offshore provides an acceptable buffer zone to prevent mortality with the possible exception of during migration [20]. Migration patterns are not well studied, so further work may need to be done to map the exact routes taken, and turbines may need to be curtailed during the migration season. A total of 61 fish species within the Great Lakes are considered threatened or endangered, with 39 being listed within Wisconsin [21]. The wind farm location has not been identified as a critical habitat for any of these species, but steps should be taken, particularly during foundation installation, to minimize habitat impact. Possible mitigation strategies include acoustic deterrent devices, bubble curtains, and an optimized soft start [22] [23]. Vibratory pile driving techniques produce less noise and may also be possible, but research into this technique is ongoing and we are not certain it will be viable in our soil type [24].

2.3 Site Design

Design of the site was performed with the aid of Continuum wind software to analyze the annual expected power based on our turbine selection and wind resource data. The site design consists of 36 V136-3.45 MW turbines distributed along a 4 by 9 grid across a 3.6km by 7.8km area oriented to maximize turbine spacing in the predominant wind direction. A wind rose showing the predominant wind direction can be found in Figure 3, and the site layout is shown in Figure 4. Turbine selection was limited by installation vessel transportation requirements. A WTIV such as the Charybdis exceeds Seawaymax dimensions and would not be able to pass through the locks of the St. Lawrence Seaway [25]. Since the Great Lakes are unlikely to see 5 years with 500MW of annual installation as required to justify the construction of a dedicated WTIV, turbine size would be limited to 6MW turbines designed for onshore use [26]. The turbines selected must also have excellent cold weather capabilities, which will be critical given the icy climate. With these criteria in mind, a range of onshore turbines rated for medium wind classes were analyzed, and the V136-3.45 was found to best meet site requirements, producing a high capacity factor without sacrificing power during windier conditions. Further optimization of our farm layout and number of turbines will occur in conjunction with the financial analysis currently in progress.

2.3.1 Lakebed Analysis

Analysis of the lakebed within our area contributed to the selection of our farm boundaries since lakebed depth and composition are critical to foundation selection. The lake bottom in our area varies from 47 to 59 m and consists of a hard substrate classified as a shallow bathyal plain. At this depth and for a firm seabed, jacket or tripod-style foundations are typical. Because of the presence of freshwater ice, we anticipate a tripod foundation will be optimal because of the lower cross-section at the waterline, which presents less opportunity for ice blockage. As a wind farm in an area with such significant ice presence has not been attempted before, significant testing will need to be conducted to analyze the impact of ice flow on the foundation substructure.



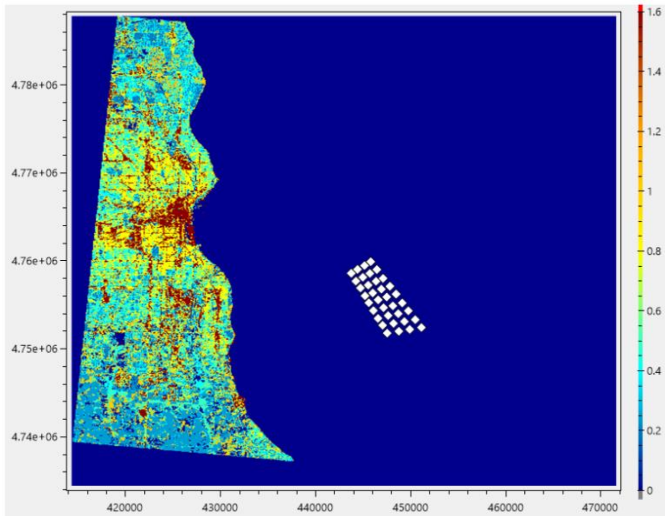


Figure 3&4. Wind rose and plot of surface roughness in the region off the coast of Minneapolis around our wind farm with turbine locations marked. The lake has low surface roughness.

2.3.2 Power Output Analysis

To determine expected annual power over the lifetime of the farm we used site information from the wind atlas to produce long-term averages along with data collected by a NOAA meteorological tower located 14 miles from our site at the port of Milwaukee [27]. The meteorological tower provides wind speed and direction time series data in 5-minute intervals going back to 2002. Along with surface roughness and topography data, this was used to create an interpolation that describes the wind speed at the farm as a joint probability table. The probability table was imported into Continuum along with geographic information describing turbine locations as well as topography and surface roughness in the surrounding area [28]. A power curve for the V136-3.45 MW turbine was found, which allowed us to perform turbine gross output calculations to determine site-specific energy production [29]. A Monte-Carlo exceedance model generated a probabilistic description of other losses such as turbine availability, wind data variability, and extreme weather events, which was used along with a wake loss to generate our wind farm net annual power output over a 20-year span. An example of the wake loss model is shown in Figure 5. Iteration was performed on wind farm parameters including turbine quantity, spacing, grid orientation, and size before reaching the current preliminary design. With the current configuration, each turbine has an average loss of 2% due to wake effects and 10% due to other effects. A total net annual expected power of 535 GWh was found, resulting in a total expected capacity factor of 49%. Turbines from other manufacturers across a variety of sizes and diameters were also analyzed using the same method. Where publicly available data was unavailable, NREL reference power curves were used as a substitute [30]. Many turbines designed for high wind speeds use a higher specific power such as the V126-3.45 or NREL 155-6 and suffer from low capacity factors in our area. In comparison, designed for lower wind speeds have lower specific power and fail to capture all of the available energy at the site, limiting generation potential. The V136-3.45 was found to have the best balance of these considerations.

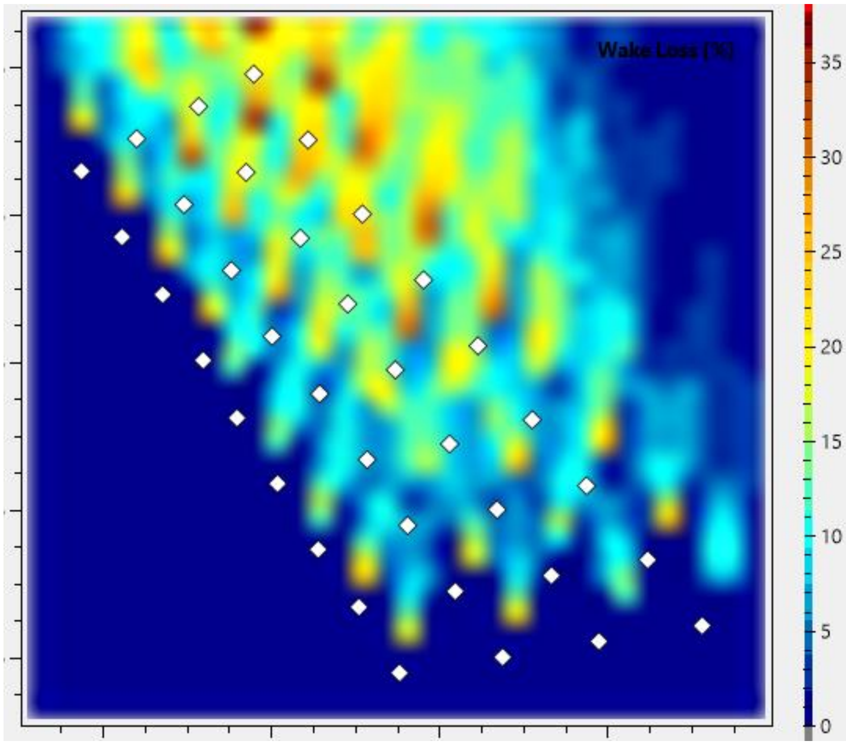


Figure 5. Plot of wake loss across the area of proposed farm during typical conditions with wind from the south.

2.3.3 Transmission Considerations

Transmission and grid capacity limits are a significant concern in the area around the Great Lakes as the Midcontinent Independent System Operator (MISO) has suffered from significant congestion in recent years, leading to curtailment of wind farm production [31]. See Figure 6 for a map of grid congestion in the area. While MISO is working on a number of projects to mitigate these issues, steps should still be taken to minimize potential disruption to the farm's interconnection [32] [33]. During the initial siting process, high-voltage transmission lines were mapped, and we observed that while potential sites in Lake Superior and Northern Lake Michigan may have strong wind resources, they did not have sufficient access to transmission to be viable without significant grid expansion. Sites in Southern Lake Michigan had better access to transmission in general, and our selected site near Milwaukee has the particular advantage of being located offshore from the Oak Creek coal power plant, which will be shutting down in 2024 [34]. This frees up 1.1 GW of transmission capacity to be replaced by clean energy produced by our wind farm. The other two sites in Southern Lake Michigan are located near the Palisades and DC Cook nuclear power plants [35]. The Palisades plant has been shut down; however, efforts are underway to restart it, so there is not a clear outlook on whether this is a viable interconnection location [36]. The DC Cook plant is certified through 2034 and does not present the same opportunity to fill lost grid capacity. Transmission lines from the farm are less than 15 miles, so high-voltage AC lines will be used as they are most cost-effective at this range [37].

2.3.4 Infrastructure Requirements

Significant infrastructure is required for the installation, operation, and maintenance of an offshore wind farm, both in terms of port capacity and vessel requirements. The Great Lakes have a particularly unique set of infrastructure concerns as there is limited access through the Saint Lawrence Seaway, which prevents many large ships from passing through. Vessels must also either be Jones Act compliant or utilize feeder vessels. Matching turbine selection and farm design to anticipated infrastructure was a key design element. There are three main installation approaches which could be developed within the Great Lakes. The first would be the use of a vessel small enough to meet Seawaymax requirements which would not be limited to remaining within the lakes. However, such a vessel would likely be limited to installing smaller turbines under 6 MW [38]. A currently existing example is the RD MacDonald, which is certified up to 3.6 MW. Next, a WTIV could be built larger than Seawaymax and remain confined within the lakes. The Great Lake's shipbuilding capabilities are likely sufficient to manufacture a large WTIV, but economically there is not a sufficient level of future projects to support this level of investment [26]. Finally, the use of floating foundations, which can be pre-assembled in port and towed to their final location, would only require tugboats already widely available. These foundations would be well suited for deeper waters near the center of the lake, opening up significant development potential. This is an attractive option for long-term development, but it would require port improvements to support the pre-assembly, and floating foundations are still a new technology with significant uncertainty [39]. Floating foundations would need to come down in cost for this to be a viable option. As a first step, the use of installation vessels which can navigate the St. Lawrence Seaway can demonstrate the feasibility of operating in the Great Lakes and confine technological risk to the challenge of dealing with freshwater ice rather than attempting to solve issues with both floating foundations and ice impact simultaneously. Once these barriers have been overcome, an increased level of investment would justify a dedicated WTIV or, more likely, port improvements to allow the pre-assembly of floating foundations. For the selected fixed foundation approach, the Port of Milwaukee likely only needs minor improvements to support assembly and installation operations, as it already has sufficient laydown space and heavy lift capabilities [40]. Chicago and Indiana-Burns Harbor are also able to supplement Milwaukee if required.

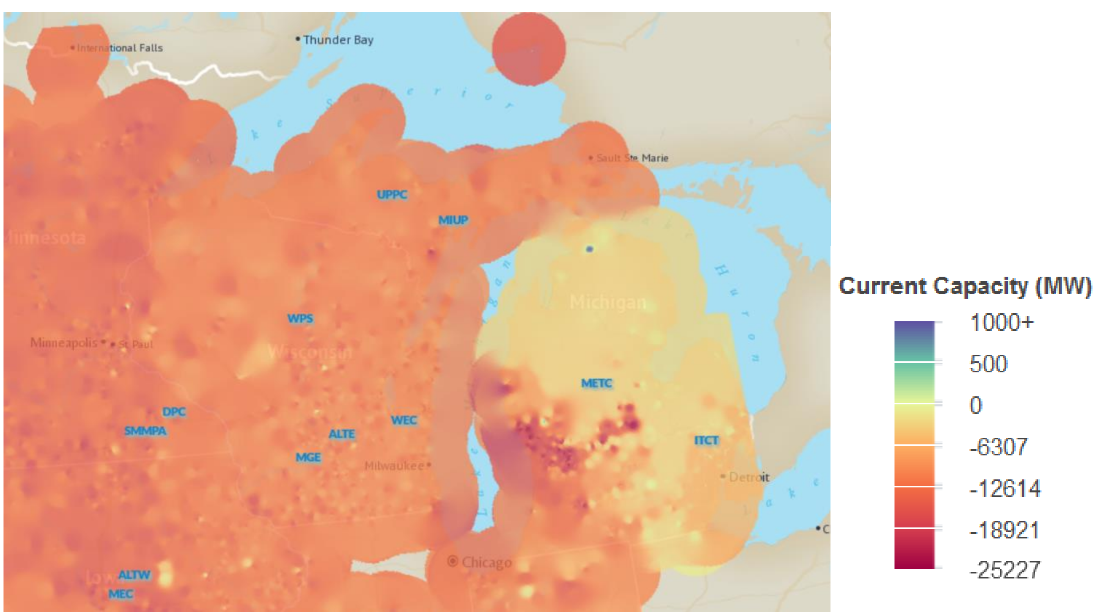


Figure 6. Map of MISO interconnection points showing limited capacity for additional power transmission due to high levels of grid congestion.

3 Financial Analysis

3.1 Expense Analysis

3.1.1 Capital Expenditure

The Wind Project's Capital Expenditures total to $752,243,166.8 over a period of twenty years. A significant majority of that, $352M, comes from the first three years of construction. This is due to significant costs in materials and siting. Then, the project will spend approximately 20.3M every year for upkeep and maintenance of turbines. This is due to Bond payments, development fees, hard costs/contingency, and upkeep. These initial capital costs are shown in Table 1.

Table 1. Estimation of Capital Expenditure costs

	Category	Total	$/kW	%
Financing Costs	Decommisioning	$6,400,000.00	$51.61	1.82
	Misc Fees	$394,128.00	$3.18	0.11
	Development Fees	$36,800,000.00	$296.77	10.45
Turbine Costs	Nacelle	$115,432,258.00	$930.91	32.77
	Blades	$34,548,387.00	$278.62	9.81
	Tower	$26,419,354.00	$213.06	7.50
Other Costs	Land	$12,500,000.00	$100.81	3.55
	BoP	$19,706,400.00	$158.92	5.60
	Foundation	$48,133,830.00	$388.18	13.67
	Electrical	$36,687,450.00	$295.87	10.42
	Install	$15,190,000.00	$122.50	4.31
Total	-	$352,211,807.00	$2,840.42	100

3.1.2 Operation Expenditure

The Operating Expenses of the project total to 36312800.21 over a period of 20 years. This originates from building utilities, repairs and maintenance, salaries and wages, insurance, property tax, and the grid balancing fee. This is expected to appreciate at a rate of +1.5% a year. This total averages to around 1.8M a year in the project lifespan.

A majority of the expense comes from paying the principal back at y20 on the green bonds, which means the NPV of the green bond's principal is discounted to 208m at end of project. This is a significant competitive advantage compared to borrowing the full amount from sponsors, as it allows the

3.2 Financing Plan

We are using a issuance of Green Bonds at a 3.00% interest rate. These Green bonds are income tax free, which creates a lower interest rate. We will pay interest on debentures semi-annually beginning at the start of the bond term [proj start date]. The maturity date is [proj end date], at which time the principal will be paid off. The debenture will be unsecured senior obligations, and rank equally with other senior indebtedness from time to time outstanding. The senior debentures will be only unregistered form of minimum indebtedness of $2,000 and in integral multiples of $1,000 in excess thereof. The senior debentures are a new issue of securities with no established trading market, and will not be listed on exchange.

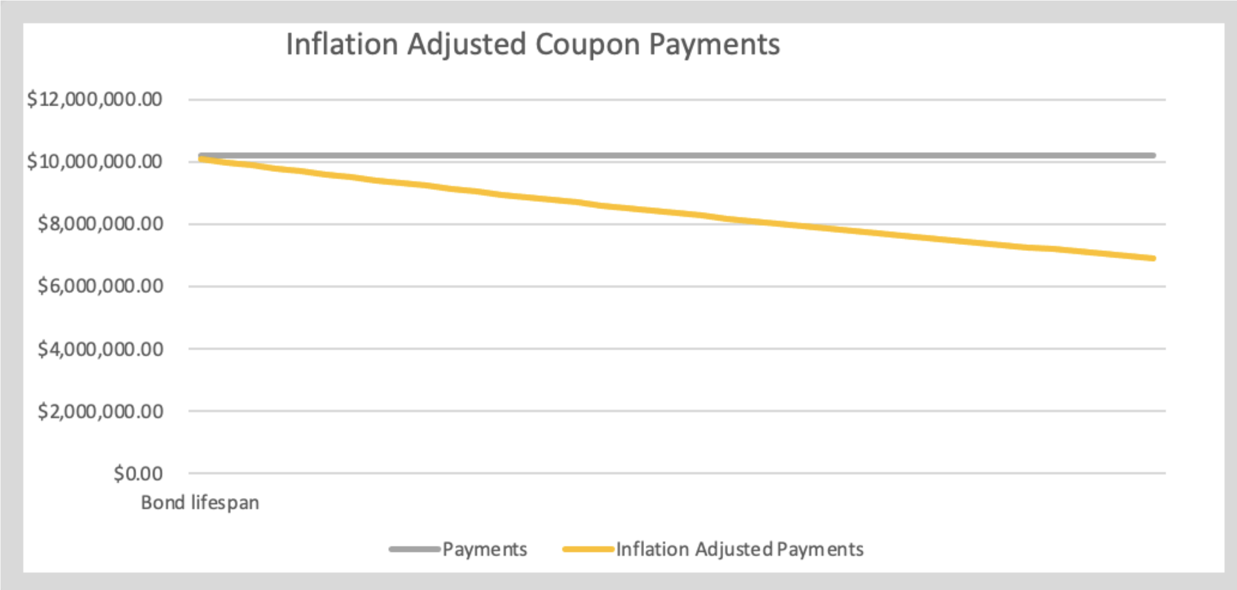


Figure 7. Analysis of Bond Coupon Payments with inflation adjustment

A majority of the expenses comes from paying the principal back at y20 on the green bonds, which means the NPV of the green bond's principal is discounted to 208m at end of project. This is a significant competitive advantage compared to borrowing the full amount from sponsors, as it allows the project to repay the principal at the end of the project, which is in line with the issuance. Underwriting discount will be .875% of outstanding debentures, totaling to $2,625,000 to be paid on issuance, on All or None basis (AON).

Table 2. Green Bond Financing plan

	Per Debenture	Total
Offering Price	99.668%	$299,004,000
Underwriting Discount	0.875%	$2,625,000
Proceeds	98.793%	$296,379,000

4. Market Conditions and Incentives

The average selling price for electricity in the larger Great Lakes area (specifically Wisc.) is $0.11/kWhr. Further incentives for our project are the ITC and PTC tax credit. The PTC credit is applicable to write off for $.03 kWh generated, to write off on equipment for up to 10 years after the project has started. The ITC credit is for development costs and is 26% of development costs for the project. This leads to a 9.463M positive credit for the project, which will be used to pay taxes after the time to earn credits is concluded for the project.

Tax Calculations						
ITC Tax Credit	$0.26	$3,448,153.28	$2,561,832.00	$2,561,832.00	$0.00	$0.00
PTC Tax credit (10 years after equip)	$0.03	$0.00	$0.00	$0.00	$8,456,457.24	$8,413,962.48
Wisconsin Corporate Income Tax	$0.08	-$76,970.69	-$64,092.87	-$65,054.27	-$3,195,749.80	-$3,275,944.33
Credits Earned		$3,448,153.28	$2,561,832.00	$2,561,832.00	$8,456,457.24	$8,413,962.48
Credits Deducted Towards Taxation (+ is rolled)		$3,371,182.59	$2,497,739.13	$2,496,777.73	$5,260,707.44	$5,138,018.15
Money Owed on Taxes (Positive means that Credits cover)		$9,463,208.73				

Figure 7. Analysis of Tax credit availability and tax burden.

5 Final Site Design

The final site design consists of 36 Vestas V136-3.45 wind turbines 11 miles South-East of Milwaukee. The farm has a rated power of 124 MW, with a capacity factor of 49% has an AEP of 535 MWh. This farm is in waters ranging from 45-60 meters deep allowing fixed bottom foundations to be used. The turbines are distributed in a 4 x 9 grid aligned to minimize wake losses, taking up an area of 3.6km by 7.8km. High voltage AC lines will be used to transmit power from the farm to the Oak Creek coal power plant which is currently undergoing decommissioning. This will serve as a convenient point of interconnection as it is already serviced by high voltage transmission lines. We have carefully selected our turbine size based on limitations to port infrastructure, specifically working around the limitations of the St. Lawrence seaway. The Port of Milwaukee is the most convenient location for staging and operations with sufficient laydown space for our needs, but Chicago and Indiana-Burns Harbor are also available to support if needed.

6 Proposed Bid Price

Using NPV (Net Present Value) of FCF (Free Cash Flow), our project can be valued at different points in time to give an accurate bid price. Then, a historic premium will be applied for bid/sell, to account for market risk [41]. Based on this analysis we are proposing a maximum bid price of $11.8M.

Table 3. Analysis of NPV used to determine acceptable bid price.

Year	1
NPV Proj.	$393,166,737.24
Max % of NPV	3%
Land Bid	11.795M

Clean Hydrogen Production Plan

Development of the farm and site plan also considered how it would fit into the Department of Energy's broader goals. The DOE's Justice40 campaign aims to provide 40% of the overall benefits of energy investment to Disadvantaged Communities (DACs). By incorporating a hydrogen production and storage facility in the industrial area formerly occupied by the Oak Creek Power Plant, we can target the goals of decreasing energy burden and increasing clean energy jobs, job pipelines, and job training for individuals in DACs [41]. There are at least 18 tracts designed as DACs in the Racine and Kenosha areas, representing a population of 73,000, as well as many more throughout the Milwaukee area [42]. The households subject to the greatest energy burden are disproportionately Black or Hispanic, often in areas historically subject to "redlining" housing policies [43]. Reducing the cost of electricity in the area will, therefore, have an outsized positive impact on these communities. Building out clean hydrogen facilities will smooth out wind turbine production and reduce costs. This would also support the U.S. National Clean Hydrogen strategic pathway by developing Milwaukee as a regional hub for clean hydrogen, targeting high-impact end uses. The Milwaukee area supports a significant manufacturing industry, which is seeing large growth in chemical manufacturing [44]. The use of hydrogen in chemical manufacturing is a high-impact application and may be one of the first sectors to transition to green hydrogen in the near term [45]. The Regional Clean Hydrogen Hubs Program is establishing 6 to 10 regional hubs for clean hydrogen throughout America to form a foundation for a nationwide network. As part of this program, the Midwest Alliance for Clean Hydrogen has been awarded $1 billion to accelerate the production and use of clean hydrogen, which our site could benefit from [46]. Other storage options for our site were also considered including batteries and pumped hydro, but hydrogen production, storage, and distribution system was the best fit for the characteristics of our area given the limited topographic options for pumped hydro, and the synergy between hydrogen and chemical manufacturing. Co-location of renewable production was also considered, but the region has relatively weak solar and wave resources, so this was not a competitive option compared to developing clean hydrogen facilities [47] [48].

References

[1] Global Wind Atlas, "Global Wind Atlas," June 2023. [Online]. Available: https://globalwindatlas.info/en. [Accessed 14 October 2023].

[2] C. Anderson, Wind turbines : theory and practice, New York: Cambridge University Press, 2020.

[3] National Renewable Energy Lab, "Offshore Wind Market Report: 2023 Edition," U.S. Department of Energy, 2023.

[4] ICF, "Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations," U.S. Department of the Interior Bureau of Ocean Energy Management, 2020.

[5] National Geophysical Data Center, "Bathymetry of Lake Michigan," National Geophysical Data Center, NOAA, 1996.

[6] R. G. Sullivan, L. B. Kirchler, J. Cothren and S. L. Winters, "Offshore Wind Turbine Visibility and Visual Impact Threshold Distances," *Environmental Practice,* vol. 15, no. 1, pp. 33-49, 2013.

[7] U.S. Geological Survey, "US Protected Area Database," [Online]. Available: https://www.usgs.gov/programs/gap-analysis-project/science/protected-areas. [Accessed 24 November 2023].

[8] A. Wei, "A Spatial Analysis of Fish Habitats in Coastal Wetlands of the Laurentian Great Lakes," McMaster University, Hamilton, 2002.

[9] Office of Coast Survey, "Electronic Navigational Charts," NOAA, 2023.

[10] Office of Coast Survey, "Wrecks and Obstructions Database," NOAA, 2016.

[11] Geospatial Management Office, "Homeland Infrastructure Foundation-Level Data," US Department of Homeland Security, 2022.

[12] C. Riseng, K. Wehrly, L. Wang, E. Rutherford, J. McKenna, L. Johnson, C. Castiglione, D. Infante, S. Sowa and R. Goodspeed, "Great Lakes Aquatic Habitat Framework," [Online]. Available: https://www.glahf.org/. [Accessed 23 November 2023].

[13] U.S. Environmental Protection Agency, "Great Lakes Areas of Concern," September 2021. [Online].

Available: https://www.epa.gov/great-lakes-aocs. [Accessed 2023 October 2023].

[14] NOAA - Great Lakes Environmental Research Laboratory, "Great Lakes Ice Cover," 02 10 2023. [Online]. Available: https://www.glerl.noaa.gov/data/ice/#overview. [Accessed 13 10 2023].

[15] U.S. Army Corp of Engineers, "Wave Information Study," 11 October 2023. [Online]. Available: https://wis.erdc.dren.mil/index.html. [Accessed 13 October 2023].

[16] E. Rau, L. Vaccaro, C. Riseng and J. G. Read, "The Dynamic Great Lakes Economy Employment Trend from 2009 to 2018," Sea Grant Michigan, 2020.

[17] Center for Biological Diversity, "Map: U.S. Threatened and Endangered Species by County," [Online]. Available: https://www.biologicaldiversity.org/programs/population_and_sustainability/T_and_E_map/. [Accessed 12 December 2023].

[18] U.S. Fish & Wildlife Service, "Land-based Wind Energy Interim Voluntary Guidance for the Northern Long-eared Bat," 2023.

[19] U.S. Fish & Wildlife Service, "Indiana Bat Section 7 and Section 10 Guidance for Wind Energy Projects," 2011.

[20] M. L. Stantial, "Flight Behavior of Breeding Piping Plovers: Implications for Risk of Collision with Wind Turbines," State University of New York College of Environmental Science and Forestry, Syracuse, 2014.

[21] Wisconsin Department of Natural Resources, "Wisconsin's Endangered and Threatened Species List," Junes 2021. [Online]. Available: https://dnr.wisconsin.gov/topic/EndangeredResources/ETList. [Accessed 12 December 2023].

[22] A. Tsouvalas and A. Metrikine, "Noise reduction by the application of an air-bubble curtain in offshore pile driving," *Journal of Sound and Vibration,* vol. 371, pp. 150-170, 2016.

[23] M. A. Ainslie and A. M. V. Benda-Beckmann, "Optimal soft start and shutdown procedures or stationary or moving sound sources," in *European Conference on Underwater Acoustics*, Edinburgh, 2012.

[24] S. Giridharan, E. S. Dieter Franz and C. Moormann, "Numerical prediction of the installation of vibratory monopile foundations for offshore wind energy projects," in *Numerical Methods in Geotechnical Engineering 2023*, London, 2023.

[25] The St. Lawrence Seaway management Corporation, "Seaway Handbook," 2023. [Online]. Available: https://greatlakes-seaway.com/en/commercial-shipping/seaway-handbook/. [Accessed 5 December 2023].

[26] Douglas Westwood, "Assessment of Vessel Requirements for the U.S. Offshore Wind Sector," U.S. Department of Energy, 2013.

[27] NOAA - Great Lakes Environmental Research Laboratory, "Milwaukee, WI Meteorological Data," Office of Oceanic and Atmospheric Research, [Online]. Available: https://www.glerl.noaa.gov/metdata/mil/met1m.php. [Accessed 27 November 2023].

[28] U.S. Geological Survey - National Geospatial Program, "The National Map - 3D Elevation Program," [Online]. Available: https://index.nationalmap.gov/arcgis/rest/services/3DEPElevationIndex/MapServer. [Accessed 27 November 2023].

[29] S. Matysik and L. Bauer, "Wind-Turbine-Models," [Online]. Available: https://en.wind-turbine-models.com/. [Accessed 4 December 2023].

[30] National Renewable Energy Lab, "NREL Turbine Archive," 2020. [Online]. Available: https://nrel.github.io/turbine-models/index.html. [Accessed 4 12 2023].

[31] K. Lydersen, "Grid congestion a growing barrier for wind, solar developers in MISO territory," Energy News Network, 29 September 2020. [Online]. Available: https://energynews.us/2020/09/29/grid-congestion-a-growing-barrier-for-wind-solar-developers-in-miso-territory/. [Accessed 7 12 2023].

[32] M. Hughlett, "Minnesota utilities spending $130M to improve wind energy transmission," Star Tribune, 28 September 2023. [Online]. Available: https://www.startribune.com/minnesota-utilities-spending-130-million-to-improve-wind-energy-transmission-great-river-energy-xcel/600308291/. [Accessed 5 November 2023].

[33] North American Reliability Organization, "2023 Summer Reliability Assessment," Electric Reliability Organization , 2023.

[34] WE Energies, "We Energies announces new timeline for Oak Creek plant retirements," 23 June 2022. [Online]. Available: https://news.we-energies.com/we-energies-announces-new-timeline-for-oak-creek-plant-retirements/. [Accessed 7 December 2023].

[35] U.S. Nuclear Regulatory Commission, "Palisades Nuclear Plant," 17 August 2022. [Online]. Available: https://www.nrc.gov/info-finder/reactors/pali.html. [Accessed 6 December 2023].

[36] Reuters, "Holtec enters power purchase agreement to reopen Michigan nuclear power plant," 12 September 2023. [Online]. Available: https://www.reuters.com/business/energy/holtec-enters-power-purchase-agreement-reopen-michigan-nuclear-power-plant-2023-09-12/. [Accessed 6 December 2023].

[37] X. Xiang, M. M. C. Merlin and T. C. Green, "Cost analysis and comparison of HVAC, LFAC and HVDC for offshore wind power connection," in *12th IET International Conference on AC and DC Power Transmission*, Beijing, 2016.

[38] W. Musial, R. Green, E. DeMeo, A. Cooperman, S. Housner, M. Marquis, S. MacDonald, B. McDowell, C. Hein, R. Rolph, P. Duffy, G. R. Zuckerman, O. Roberts, J. Stefek and E. Rangel, "Great Lakes Wind Energy Challenges and Opportunities Assessment," National Renewable Energy Laboratory, Golden, CO, 2023.

[39] U.S. Department of Energy, "Floating Offshore Wind Shot," 23 February 2023. [Online]. Available: https://www.energy.gov/eere/wind/floating-offshore-wind-shot. [Accessed 5 December 2023].

[40] Port Milwaukee, "Por Milwaukee Heavy Lift Capabilities," 2020. [Online]. Available: https://portmilwaukee.com/Port-Mke/Commercial-Services/Heavy-Lift. [Accessed 3 December 2023].

[41] S. D. Young, B. Mallory and G. McCarthy, *Interim Implementation Guidance for the Justice40 Initiative*, Washington, D.C.: Executive Office of the President: Office of Management and Budget, 2021.

[42] Council on Environmental Quality, "Climate and Economic Justice Screening Tool," 22 November 2022. [Online]. Available: https://screeningtool.geoplatform.gov/en/about. [Accessed 10 December 2023].

[43] Sierra Club, "Energy Burden in Milwaukee: Study Reveals Major Disparities & Links to Redlined Areas," Milwaukee, 2021.

[44] B. Mayborne, "State of Manufacturing in Metro Milwaukee," Metropolitan Milwaukee Association of Commerce , Milwaukee, 2022.

[45] Hydrogen Interagency Task Force, "U.S. National Clean Hydrogen Strategy and Roadmap," U.S. Department of Energy, 2023.

[46] L. Thompson, "Department of Energy awards Argonne National Laboratory and partners up to $1 billion to launch clean hydrogen hub in the Midwest," Argonne National Laboratory, 2023.

[47] Solargis, "Global Solar Atlas 2.0," September 2023. [Online]. Available: https://globalsolaratlas.info/. [Accessed 8 December 2023].

[48] D. V. Sogut, A. Farhadzadeh and Robert E. Jensen, "Characterizing the Great Lakes marine renewable energy resources: Lake Michigan surge and wave characteristics," *Energy*, vol. 150, pp. 781-796, 2018.