Project Development Report

Texas Tech University & South Plains College

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**Abbreviations for listed fields of study:*
RE – Renewable Energy
CE – Civil Engineering

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Executive Summary

This is the final development report for Techsan Wind Teams (TWT) 50 turbine, 1.1 GW nameplate capacity wind project located in Lake Michigan, approximately 38 km from the city of Milwaukee. The report outlines the selection of the chosen site, presents wind resource analysis, outlines the rationale for turbine and foundation selection, and the grid interconnection requirements. Further, logistical, environmental concerns, site activity issues, and economic factors are presented for consideration during the development planning phase. Various development considerations at the site location are outlined below.

1.0 Site Description

1.1 Site Selection

The Techsan Wind Team (TWT) was tasked with developing an economically viable and technically feasible project in the Great Lakes region of the United States. The TWT began by identifying average wind speeds in Lake Superior and Lake Michigan, the two lakes specified for development, using a map provided by the National Renewable Energy Laboratory. From there, other factors were considered including environmental, bathymetric, existing infrastructure, market size, climatic factors, and considerations for construction. This analysis led to Lake Superior being ruled out for this project, owing in large part to the lack of existing infrastructure on the Upper Michigan Peninsula such as high-capacity transmission lines, rail systems, and port infrastructure, which were analyzed using Geographic Information System (GIS) tools, as well as publicly available databases. Lake Superior also has a low electricity demand, due to a lack of large population centers and heavy industry. The coastlines of Lake Superior house less than 500,000 U.S. residents, while the coastlines of Lake Michigan house about 12 million. By building in Lake Michigan, more direct access to electricity markets would be achieved. Lake Superior freezes over 75% almost every winter,[1] making maintenance difficult. This would also put a strain on the foundation as Lake Superior is much deeper than Lake Michigan and make ice deterrence technically difficult. Developing the project on Lake Michigan gives access to existing road, rail, port, and electrical infrastructure through fossil fuel power plants that will be decommissioned. Further analysis of Lake Michigan[2] shows an area of approximately 2,700 km^2, shown in Figure 1, that has favorable conditions for wind development.

Figure 1. Area of most favorable development conditions in Lake Michigan.

1.2 Site Characteristics

The TWT project is located approximately 32 km from the Wisconsin shoreline, 38 km from the chosen port, and 45 km from the point of interconnect (POI). Being 32 km from shore, the turbines will have minimal visual impact from the shoreline with an average visibility rating of 2.1 on a 6.0 scale.[3] The turbines will not be visible from Michigan, Illinois, and Indiana. Bathymetry data, collected from three sources, indicates a depth of 80 m in the project area, with some points exhibiting shallower depths.[1][2] The average significant wave height was found to be 1.1 m and the surface roughness length is 0.1 mm.[7][8] The water temperature averages between 21.9° C as a high and 1.9° C as a low.[9] The average snow and sleet precipitation is 138 cm per year, with approximately 89 cm being snow.[10] The average rainfall per year is approximately 68 cm, for a total annual precipitation of 206 cm.[10] This results in a Koppen-Geiger Climate Classification of Dfb, snow, fully humid, with a warm summer.[11] The lakebed consists of soft soils with shallow bedrock such as Haplosaprists and Haplufdalfs,[12] which impacts foundation selection. According to the American Society of Civil Engineers ASCE 7 Hazards Report, based on the location, soil type, and the fact that this is a power generation facility, the turbines should be constructed to withstand a 10 and 25-year wind speed Mean Recurrence Interval of 32.6 and 35.8 m/s, respectively.[14] Ice storms are infrequent in southern Wisconsin and are more common in the northwest and north-central region at a rate of 3-5 per year and a significant ice storm every 5 years.[13] Milwaukee has an extended severe weather and tornado season from late May to early June, but these are more common inland.[15] The project area is 50 km^2 and is expected to experience approximately 15 lightning strikes per km^2 per year, or approximately 750 lightning strikes per year, classifying it as “relatively moderate” on the National Lightning Detection Network’s scale.[14] Furthermore, the area experiences an average of 74 days/yr that are at or below freezing;[5] this could lead to icing events that decrease turbine performance.

1.3 Wind Resource and Surface Conditions

Three sources of data were used to create a complete data set to work with. The MERRA-2 and the ERA5 meteorological aggregate models, which have wind speed and wind direction at 50 and 100 m respectively, and temperature at 2 and 10 m, as well as the NOAA National Data Buoy Center station 45007,[16] which measures wind speed at 3.6 m and wave attribute data, were used. The meteorological models have data with 1 hour temporal resolutuoin from 1980 through 2023 and the buoy since 1981. An advantage of using meteorological models is that they can continuously model data during freezing events while a buoy can occasionally ice over, reducing its data availability. All data was quality controlled and analyzed using Windographer due to its ease of use, extensive feature set, and TWT's familiarity with the software.

The average wind speed was found to be 8.9 m/s at 100 m. Using a shear exponent of 0.139 calculated using three different heights, wind speed at 140 m was estimated to be 9.65 m/s with a standard deviation of 2.42. The predominant wind direction, shown in Figure 2, at 100 m is from 200°, with most power in the wind coming from 190° .There is a predominantly southerly wind direction with a slight western bias at 50 m, as heights increase to 170 m wind backs to be more consistently southerly. According to the International Electrotechnical Commission (IEC) 61400 Wind Turbine Generator classes,[2] this high class-II wind site suits class I or II turbines.

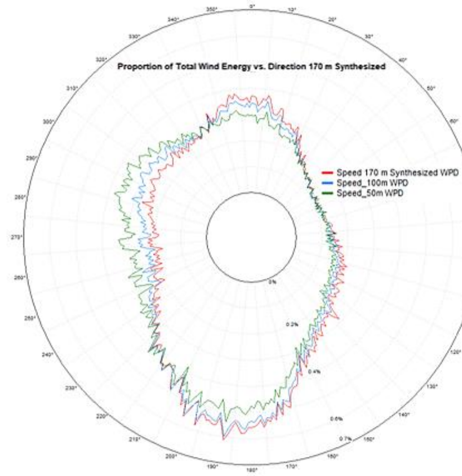

Figure 2. Wind energy rose at various heights.

The turbulence intensity (TI) for this site cannot be calculated using normal methods, which require a data set with a high temporal sampling rate, much higher than either the satellite or buoy provides. However, TI can be estimated by analyzing the site conditions. Overwater, TIs are lower than on land due to the low surface roughness of water and decrease as height increases. Using these factors, the estimated TI is 14%, class C, the lowest intensity of IEC 61400.[17] Further estimates in TI can be derived by investigating events that cause instability, such as temperature gradients, wind shear and veer, and storms.[18] One method to directly measure TI would be deploying the Uncrewed Surface Vessel from Orsted,[19] which collects in-situ data on wind generation, seabed characteristics, and marine and avian behavior. These instruments would take measures at a high enough rate to calculate the TI.

Due diligence must be conducted to determine the effects that wind projects in the area would have on the TWT project, likewise, the potential effects of TWT's project on neighboring projects must be analyzed. Wind direction and speed were analyzed in Wisconsin, Illinois, Indiana, and Michigan using Global Wind Atlas,[20] which led to wind projects of interest being identified using the United States Geological Survey Wind Turbine Database[21] and GIS tools. This analysis shows no large concerns, however, there is one wind project downwind of TWT's project, the Lake Winds project, operated by Consumer Energy in Mason County Michigan.[22] It is a 101 MW capacity project using 56 Vestas V100-1.8 MW turbines, and is 115 km northeast of TWT's project. The Lake Winds project is not directly downwind of the 190° wind direction measured in TWT's project area, and at 115 km away it is unlikely that wakes will affect the existing project measurably. However, studies have shown that wind turbine wakes over water can propagate as turbulence or reduced wind speeds over 100 km away.[23][24] With this in mind, TWT will notify and work with the Lake Winds project to measure for and potentially mitigate these effects through turbine level generation reduction, curtailment, or by utilizing wake steering.

1.4 Site Activity

The coastal regions of Wisconsin, Michigan, and Illinois along Lake Michigan feature various key locations that warrant attention during the planning of wind project developments. Military and federal docks, such as the Naval Station Great Lakes, typically experience low traffic levels and are not expected to significantly impact the project. Conversely, touring companies operate multiple routes along the coast and into deeper waters, which may necessitate further consideration.

Given that the turbines will exceed a height of 499 feet, notification to the Federal Aviation Administration (FAA) and acquisition of a permit will be necessary.[25] The FAA mandates appropriate lighting for structures taller than 200 feet to ensure visibility to aircraft operating in the vicinity. As the Milwaukee airport is 40 km from the project, they will need to be consulted to ensure this project does not interfere with their operation. However, flight maps show few flights leaving Milwaukee airport in the direction of the project. The flights that do go over the project area are typically already at a cruising altitude of 30,000 ft.

A NexRad Radar is located at 108th and 6th Mile Road, 56 km from the project according to GIS data. The project could impact the radar as spinning blades can cause interference on the radar. However, adjustments can be made to remove this interference. In extreme weather conditions where radar readings are critical, turbines can be curtailed while measurements are taken. TWT also analyzed microwave corridors and found no conflicts as microwave communication towers are limited to 64 km of range, which the width of Lake Michigan exceeds.

Military activities can be a critical factor in wind development, as the Department of Defense (DoD) Clearinghouse has the authority to halt projects for reasons of national security. There is a DoD training range, designated as range 6903, located roughly 30 km west of the project area.[26] Spanning 746 square-kilometers between Port Washington and Manitowoc, Wisconsin, this area is recognized as restricted DoD airspace. Although there are considerations for this region to become a naval testing site in the future, its distance from the project renders it a non-issue. Additionally, within Illinois's borders, there is a one-mile restricted zone off the coast of Chicago for the Great Lakes Naval Station,[27] which poses no issues.

Additionally, Lake Michigan is a hub of industrial activity, necessitating the consideration of shipping vessel traffic. Shipping lanes have been analyzed, and a buffer zone of two nautical miles has been established around each lane, providing sufficient space for vessels to maneuver around and through the project site if required.[28] The site was chosen in large part due to the low cumulative stress of the area, as shown in Figure 3.

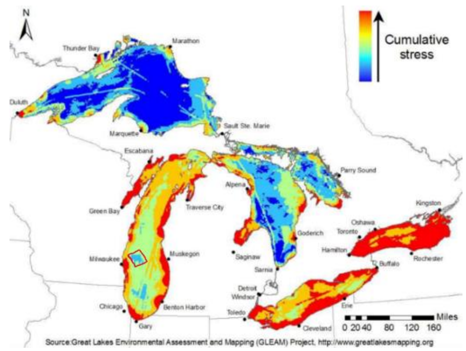

Figure 3. Cumulative stress map.

The project area was analyzed for potential underwater obstructions and shipwrecks using the NOAA Automated Wreck and Obstruction Information System and Electronic Navigational Charts. These resources identified a point of interest for the project—the Lumberman shipwreck.[29] Located 53 m below the surface and situated 6.5 km from the POI at the WE Energies Oak Creek Power Plant, this shipwreck necessitates planning to avoid disturbances when laying transmission lines from the project's offshore substation to the shore.

To take part in the Justice40 Initiative,[30] the TWT will intentionally seek out members of disadvantaged communities to fill the roles necessary for the operations and maintenance of the project. Many areas of Milwaukee are classified as a disadvantaged community and by including these members in the project, a more equitable future can be built through renewable energy. TWT will include Native American interest groups as part of its community outreach and ensure that tribal interests are respected. As part of the Biden Administration's goals for offshore wind energy, the Floating Offshore Wind Energy Shot is set to reduce the cost of floating offshore wind energy by more than 70%, to \$45/MWh by 2035, which this project will take advantage of.[31] The Biden Administration also has a goal of deploying 15 GW of floating offshore wind capacity by 2035, which this project will address.[32]

2.0 Technical Analysis

2.1 Turbine Selection

Turbine selection is one of the most important aspects of the development process due to economic and technical factors such as capacity factor, downtime, and market availability. Based on the analyzed wind data, possible turbine choices were those within IEC class IB, as these turbines are designed to be used in wind climates like this site. The top three turbines analyzed were the GE Haliade X-14 MW[33] at 150 m, Vestas V236-15 MW[34] at 150 m, and the International Energy Agency (IEA) Reference 22 MW turbine[35] at 170 m, which are class 1B wind turbines. Simulations were run, excluding losses, based on the collected wind data. The GE and Vestas turbines have a predicted gross capacity factor of 71% and a gross single turbine Annual Energy Production (AEP) of 87,304 and 93,541 MWh, respectively. The IEA turbine had a higher gross capacity factor of 72% and a gross single turbine AEP of 139,234 MWh. This data was calculated using Windographer along with the Wind Atlas Analysis and Application Program (WAsP) so that wake interactions could be modeled within the layout and so the earlier simulation findings could be confirmed. While the IEA turbine is not in production, turbines of this size have already been announced by companies such as Ming Yang to be set for development by 2025[36] and previous IEA reference turbines have proven to be reliable indicators for future wind turbines. The IEA turbine has a 3 m/s cut-in speed, 12 m/s rated power speed, a cut-out speed of 30 m/s, a 285 m rotor diameter, a hub height of 170 m, and a direct drive generator. All specifications for this turbine are available through a GitHub repository hosted by the IEA wind task 37.[37] By the time the project is ready for construction, similar turbines are expected to be in production.

The IEA Reference 22 MW turbine was chosen for use in this project over other options because of its superior capacity factor and AEP.

2.2 Foundation Technology

Offshore wind turbine foundations can be grouped into four main categories: Gravity, Monopile, Jacket, and Floating. All four of these categories were researched for use in this project. Factors such as water depth, soil type, cost, endurance, and environmental impact were analyzed against the characteristics of these foundation types. Floating foundations were found to be the most suitable for use in this project.

The largest factor in the determination of foundation type is the depth of the Great Lakes. Though water depths are less than 50 m around the shores, making fixed bottom foundations viable, they quickly deepen to depths of over 100 m. These deeper areas of the lakes are where the highest, 9.65 m/s, wind speeds occur. When bathymetry exceeds 60 m, fixed-bottom foundations are no longer economically viable. This was the primary reason for selecting a floating foundation.

Floating foundations can be broken down even further into four main types: the tension-leg platform, spar, semi-submersible, and barge type, with an experimental hybrid design that combines different aspects of floating foundations to improve performance and reduce cost. Ultimately, the tension-leg platform was decided upon to be the foundation of choice because of the high-performance factor when compared to other foundation choices in the context of ice loading. This is also one of the cheapest foundation choices despite the foundation's relative newness.

Because freshwater ice floats more above the waterline than saltwater ice, and the fact that Lake Michigan is a freshwater lake, the expected issue of ice jamming will have to be more intentionally dealt with. Ice jamming is when ice builds up on the foundation and causes extreme loads that can damage the foundation and turbine if left unmitigated. The current most successful solution is the use of ice-breaker cones, which are cones attached to the point where the foundation meets the waterline. With the wide part of the cone facing upwards and the point entering the water, this allows for ice to be moved around and away from the foundation, meaning there will be fewer potentially damaging loads on the foundation because of ice jamming. This would decrease maintenance costs and downtime.

2.3 Grid Interconnection

The 1.1 GW WE Energies Oak Creek coal-fired power plant near Milwaukee, set for retirement by late 2025,[38] is approximately 43 km from the TWT project site. This power plant is responsible for approximately 10% of all power produced in Wisconsin. On-site, two substations connect to 230 kV and 138 kV transmission lines capable of transmitting a combined 1.1 GW within the Midcontinent Independent System Operator (MISO), supplying market access to Milwaukee, Waukesha, and Racine. Analysis of the two substations shows one larger substation with a capacity of approximately 875 MW, and a smaller substation with a capacity of approximately 224 MW. Analysis of the transmission lines from this power plant shows no conflicts with other generators, meaning the entire 1.1 GW capacity will be available. TWT proposes to acquire this plant for $20 million and repurpose its existing infrastructure for this project.[39] An added benefit of using these robust transmission lines is that within MISO, when transmission is not constrained and wind is not curtailed, the price of energy can fall by as much as $20/MWh, aiding the low cost of electricity that will be necessary for the project to receive loans and community support. In terms of additional generation costs due to transmission constraints and wind curtailment within MISO, from January 2020 to January 2023 there has been a nearly $150 million increase, with a spike to $300 million in spring of 2022.[40] The project location is well-suited for future turbine expansion and transmission infrastructure. Milwaukee is poised to benefit the most from investments in transmission lines, potentially yielding an operational profit increase of up to $20 million. As a provision of the Inflation Reduction Act (IRA) of 2022, the Grid Deployment Office has approximately $3 billion in funding for transmission build-out, including $2 billion directly for funding loans, $760 million in funding for offshore transmission development, and economic development grants for impacted communities, and $100 million specifically for offshore wind energy transmission development.[41] MISO also typically dispatches electricity from generators that are closest to the load, meaning this project would be less likely to get curtailed when the major markets of Milwaukee, Racine, and Waukesha need power, thus boosting the project’s profits. By using this decommissioned fossil fuel power plant as the project's POI, as well as the site for the hybrid generation or storage technology, TWT will qualify for the 10% energy community bonus from the investment tax credit, outlined in the Inflation Reduction Act of 2022.[42]

Another benefit of using existing transmission infrastructure is that the lengthy and expensive grid integration study can be expedited as one must have previously been done for the coal plant currently using the transmission lines. MISO favors battery projects in the grid study pipeline, meaning rather than waiting for the typical three-year period it takes to complete the study, the project could take as little as one year. Currently, the MISO generation interconnect queue consists of 1,317 projects totaling 228 GW. The east study group within MISO, encompassing Wisconsin and Michigan's upper peninsula, has only 83 of those projects totaling 12 GW, meaning that the process could once again be quicker than expected.

2.4 Site Layout

The design of TWT's 1.1 GW capacity wind project, shown in Figure 4, employs strategic turbine wake management to optimize electricity generation and reduce wear on the 50 turbines. A proper layout is crucial and hinges on careful analysis of wind patterns to set the optimal distance between turbines and rows, as well as each row's alignment.

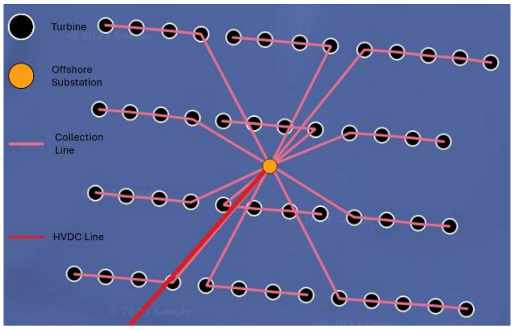

Figure 4. Project Layout

Turbine wake severity is influenced by wind velocity, surface roughness, and blade size. In environments characterized by high winds and smooth surfaces, such as the chosen lease area, wakes can extend farther and grow larger, especially with the project's use of turbines with a 285 m rotor diameter.

To mitigate wake effects, the project is laid out perpendicular to the predominant wind direction of 190°. Turbine rows are spaced ten rotor diameters (RD) apart, and 5 RD within rows, with alternating rows staggered by 2.5 rotor diameters. This configuration ensures that downstream turbines will experience reduced wake effects generated by those upstream[43] as a gap is created for the wakes to pass through and dissipate. Another advantage to staggering the rows is an area of higher wind speed is created behind the turbines, in between turbine wakes (Figure 5). By positioning the turbines to take advantage of this higher wind speed, the project can both minimize wear and increase production.

Due to the 22 MW capacity of the chosen turbine, the collection system must be designed to carry the high currents that will be generated. To reduce the current that will be running through the collection cables, the collection system will run at 69 kV and will half the current compared to a 34.5 kV collection system, thereby decreasing the heat losses associated with higher amperages. Ten collection lines will carry 88 MW, with two more strings carrying an additional turbine at 110 MW, to a floating offshore substation at the project's center. The cables connecting four turbines, 88 MW, to the substation will be 1,780 MCM cables with a capacity of 1,453 amps, yielding an economic carrying capacity (ECC) of 91 MW.[44] The cables that connect five turbines, 110 MW, to the substation will be 2,515 MCM cables with a capacity of 1,751 amps and yield an ECC of 110 MW.[2] The ECC is based on a 55% total capacity, after this point heat losses become too high in a transmission line to be economically viable. The decision to operate at high voltage and centralize the substation will decrease the cost of the collection system by limiting the amount of cabling needed.

As with all wind turbines, a pad mount transformer will be necessary. Because of the extremely high capacity of the chosen turbine, the pad mount transformer for each turbine will need to be capable of transforming 22 MW. TWT has selected a 69 kV pad mount transformer that can step up the voltage for collection. The collection system will converge at the central floating substation, where the voltage will be stepped up and rectified, transforming it to high voltage direct current (HVDC). HVDC is used in offshore power transmission scenarios when the distance is greater than 50 km.[45] HVDC is more economical than high-voltage alternating current (HVAC), as at distances below 50 km, the expense of HVDC equipment becomes less economically feasible. Despite this project being 45 km away from the POI at the WE Energy Power Plant, the extended timeline anticipated for this project will decrease the cost due to increased economies of scale and technological maturity, making HVDC more economically viable across these shorter distances. HVDC also comes with the advantage of less inductive losses due to interactions with the water and to the skin effect, and only requiring a single line to be run to shore, as it is not 3-phase power.[46] This advantage saves dredging, burying, and material costs. Failing a decrease in HVDC equipment cost, an HVAC system can be used instead to transfer power from the floating substation to the POI. The 2,200 MCM HVDC line will transmit at 345 kV and will cost approximately $7.5 million per km, for a total cost of about $337.5 million.[46] Easements will be necessary for the offshore-to-onshore substation transmission line.

2.5 Production Estimation

Production estimates for this project were calculated using WAsP at a height of 170 m. The Site Layout was imported from GIS into a topographical map of Lake Michigan, and wind data for the chosen site was imported from Windographer. Simulations were run to calculate AEP, proportional wake losses, and the net capacity factor of this project.

By running simulations multiple times, it was possible to fine-tune the site layout and achieve optimal energy production while considering cost factors. This iterative process also enabled the strategic placement of turbines within the layout, maximizing their efficiency and overall performance. The utilization of iterative simulations resulted in an optimized site configuration that balanced energy output and cost-effectiveness by precisely micro-siting the turbines within the layout. The results from this process are an AEP of 6,961,700 GWh/yr, enough to power 500,000 homes,[47] wake losses of 5.16%, and a net capacity factor of 69%.

Because of the extreme cold during the winter months, blade heating will be a necessity, as ice loading can decrease a turbine's output by as much as 80% if production is halted entirely.[48] The IEA turbine will use a tube along the leading edge inside the blade that will blow hot air to the blade tip, preventing ice and extending production.[49] Significant ice buildup on wind turbines can reduce output by up to 20%, and delay production further if damage is caused to the turbine or blades. Even light icing on the blades can reduce wind turbine output as the ice affects the aerodynamic profile of the airfoil.[50] Therefore, it is important to implement de-icing measures.

2.6 Hybrid Generation and Storage Technologies

Hybrid power generation and storage, encompassing green hydrogen production and battery storage, were considered by the TWT project to avoid curtailment, diversify revenue, and store surplus energy. The project's proximity to the WE Energies Oak Creek Power Plant on Lake Michigan's shoreline provides ample fresh water for electrolysis, producing hydrogen for storage and sale. Green hydrogen applications include acting as a store of energy, Hythane for use in natural gas plants, green steel production, and other industrial applications. Distribution would require pipelines or cryogenic tankers. The Inflation Reduction Act of 2022 incentivizes green hydrogen with a Production Tax Credit (PTC) ranging from $0.60 to $3.00 per kg, based on the carbon intensity of the production method used.[51] Calculations done using current estimates place wind energy's carbon intensity at 0.61 kg of CO2 per kilogram of green hydrogen produced, this places wind energy in the 2nd highest PTC bracket of $1.00/kg of green hydrogen produced. The TWT anticipates that by utilizing floating foundations, which use less steel than fixed bottom, using local recycled steel for the towers, and capitalizing on the higher energy production that comes from offshore wind, the project's carbon intensity will decrease to less than 0.45 kg of CO2 per kg of green hydrogen produced, therefore qualifying for the full $3 PTC. The project's fifty turbines will produce 6,961,700 MWh/yr. Since 55 kWh is needed to produce 1 kg of green hydrogen from 9 kg of water, approximately 127 million kg of hydrogen could be produced per year. This would require a total annular amount of approximately 1.14 billion kg of water or 301 million gallons. The MISO curtailment rate for wind energy is 5.5%[52] and is expected to rise as variable renewable energy penetration increases in the grid. which would inform the decision to use the project to produce green hydrogen 5.5% of the year, ~7 million kgs, rather than be curtailed with no other revenue options. A Water Withdrawal Registration form is required for new water withdrawals of 100,000 to 2 million gallons per day, which would apply to this project. A plan to use or dispose of brine produced during electrolysis would be needed as approximately 940 kg will be produced per year. However, based on logistical and technical challenges such as storage and transportation of hydrogen, TWT will not be pursuing this option. TWT has decided to employ a battery storage system and not produce hydrogen.

Battery storage, using technologies like lithium-ion batteries, will store excess energy, charging when prices are low, boosting revenue, and reducing curtailment losses. Such storage systems qualify for an Investment Tax Credit (ITC) of 6-50%.[53] A 30% ITC mandates adherence to wage and apprenticeship criteria, an additional 10% is given for projects at decommissioned fossil fuel sites in energy communities and an additional 10% is added for using U.S.-manufactured equipment. Sourcing domestically manufactured batteries was difficult in the past due to supply and cost, however, by 2030 the DOE estimates that there will be 1,000 GWh/yr of battery manufacturing capacity in the country.[54] This project will meet all the requirements to qualify for the 50% ITC, lowering the overall cost of the battery storage part of the project.

Based on a Tesla battery storage project in Angleton, TX, a 1,500 square-meter plot of land can store 200 MWh of battery storage. 7.5 square-meters can house one MWh of battery storage. Utilizing 22,500 square-meters of land located directly next to the large onshore substation, 2,925 MWh of storage can be installed with approximately 743 MW of discharge over four hours. Final battery specifications will be arrived at to mitigate the day-ahead forecasting error which is approximately 16%.[55] This will cover the uncertainty in forecasting wind energy production. The four-hour option of the Tesla Megapack was chosen compared to the two-hour option because the MISO market has a typical peak of four hours in energy prices per day. This means the batteries will discharge less power but to more people per day for a longer time compared to the two-hour option which would discharge power to more people but for a shorter time. Transmission and financial analysis informed this decision. There are also approximately six hours of blackouts in Wisconsin per year, meaning the four-hour option would be sufficient to cover these blackouts as they come up in the Milwaukee area. Ultimately, this is meant to make more money for the project. The charge/discharge cycle of the battery energy storage solution (BESS) is designed with the mean diurnal profile of the wind resource and mean demand curves for the market area in mind.[56][57] Each month has a unique charge/discharge cycle to best match these two variables and overcome their seasonal changes. Including a BESS allows for the wind project to operate at maximum capacity as reserve power requirements from MISO will be lower. This allows for increased profitability for the project.

In addition to increasing profitability for the project, the battery storage system will also provide ancillary benefits to the grid. Having energy on demand will lead to more consistent energy prices, stabilizing services for grid frequency,[58] and black start capabilities in the event of blackouts.[59]

2.7 Operations, Maintenance, and Construction

One of the most challenging aspects of this project will be the operations, maintenance, and construction of the wind project. Because of the narrow width of the locks that lead to and from the Great Lakes, it would be impossible to transport the extremely large components of offshore wind turbines to the project site unless the locks were enlarged. Overhead bridges also limit the height of components that can be transported using rivers to Lake Michigan, again making transportation impossible unless the bridges were raised or removed entirely, which is not feasible. While components are also sometimes transported using highways and roads, the extreme weight of turbine components would damage this infrastructure, thus prohibiting transportation through this method. This leaves railways, which are the cheapest form of transportation and of which the Great Lakes region has a plethora, including nearby Chicago and Milwaukee. Typical heavy axel railcars can hold up to 157 tons, not nearly strong enough for the extremely heavy components of the chosen turbine. However, the Department of Energy has designed and tested the Atlas Railcar, initially intended to transport sensitive spent nuclear fuel, capable of transporting 240 tons of cargo, which is within the limits of the chosen turbine components.[60] The approximately 600-ton nacelle will be divided into smaller component shipments that will allow for more manageable transport.

The Port of Milwaukee, more specifically Logistec, will house laydown yards and assembly stations, as well as allow the Wind Turbine Installation Vessel (WTIV) a place to port. Another benefit of the project is that it is expected to create hundreds of new construction jobs and seventy new full-time operations & maintenance jobs in Milwaukee. This port has extensive access to roads and railways, making it a hub for transportation access. Five acres will be leased from Logistec to support construction, operation, and maintenance activities. Logistec offers direct lake access and vessel loading & unloading capabilities via five cranes for a total of 181.4 metric tons of lifting capacity, open storage, and warehouse space of 285,000 square feet.[61] Though upgrades will have to be made to the port such as reinforced concrete due to the extreme weight of the components along with higher capacity cranes, this is a large head start compared to other ports that were researched in the area. Funding for these upgrades could come from the Port Infrastructure Development Program, a provision of the Bipartisan Infrastructure Law, which makes available $2.25 billion from 2022 to 2026, $450 million of which will be available in 2024.[62]

The WTIV may be the most difficult aspect of construction for this project. As previously mentioned, size constraints of the great lake locks will not allow currently existing or soon-to-be-completed WTIVs from being transported to the project site. This would necessitate that either an entirely new WTIV be built for the sole purpose of servicing Lake Michigan, a costly endeavor at around $625 million based on the Charybdis, or modifying a currently existing WTIV outside of the Great Lakes so that it could be transported in a modular format, also a costly endeavor as this would essentially require the vessel to be rebuilt. To avoid these issues, it was decided that a large crane would be constructed on the Port of Milwaukee and would assemble the turbine just offshore, the LR 1700-1.0W[63] for example, which has a 700-ton lifting capacity up to 170 m, which would then be towed out to its final position and anchored down to the seafloor. This would require three Anchor-handling Vessels (AHVs) to tow the turbine and cost about $160,000 per day. These vessels only operate when the significant wave height is below 1.5 m and wind speeds are below 14 m/s. The project is within transit distance for the vehicles. Lake Michigan generally closes to marine traffic for critical maintenance from January 15th to March 25th during the winter season as the lake freezes over and is essentially impassable due to ice. This will necessitate that construction take place outside of these times, preferably during the summer when wind speeds are lowest, and will allow cranes to operate more consistently as high wind speeds require cranes to cease operations. During the winter, when Crew Transfer Vessels (CTVs) are not able to pass through the ice to the project, helicopters will be used to transport technicians and supplies, otherwise, CTVs will be used which are cheaper.

Due to lake-effect snow, the western region of Lake Michigan and Wisconsin receives much less snow than the eastern half of Lake Michigan and Michigan. This means operations and maintenance activities should not be severely impacted during the winter months. Because of the nature of lake-effect snow as well, there is typically a boundary around the shore where snowfall is quite low, approximately one inch on average for a one-mile boundary around the shore, and then significantly higher snowfall averages outside of this one-mile boundary. Since the chosen port and POI are within the one-mile boundary, activities should be less impacted still. The port of Milwaukee has increased its ship-to-shore capacity, which allows ships to plug into shore electricity rather than run their engines at ports, which will reduce carbon emissions.

2.8 Decommissioning Plan and Future Build-out Scenario

Funds will be set aside throughout the life of the project to address decommissioning costs. This ensures a complete decommissioning process can take place at the end of the project's lifetime, to return the affected area to its original state, or to ensure that repowering may occur. Using the Cape Wind project's decommissioning plan[64] from 2014 as a guide, it is estimated that the cost of decommissioning per turbine would range from $700,000 to $1.2 million, with $1 million being the estimated true value. This puts the total cost of decommissioning at an estimated range of $35 million to $60 million, with $50 million being the estimated true total cost value. It is estimated that approximately 5-10% of the initial cost of installation per turbine can be recuperated based on the prices of steel and copper as a salvage cost.[65]

Twenty teams won the First Phase of Wind Turbine Materials Recycling Prize,[66] which is a competition run by NREL and seeks to advance the development of a cost-effective and sustainable U.S. recycling industry for wind turbine materials, 10-15% of which are considered unrecyclable such as fiberglass and rare earth elements. The results of this competition will lead to a more sustainable decommissioning of the project. This will decrease the need to extract new materials for wind turbine production, increase resiliency against price fluctuations, and decrease wind energy's environmental impact. TWT will utilize Mobile Wind Blade Recycling for Concrete from Grand Rapids, Michigan, and Rare Earth Element Production with Net-Zero Carbon Emission from West Lafayette, Indiana, to ensure that every part of the turbine is recycled. Each of these recyclers is located within 300 miles by train transport, allowing for ease of access.

For a future build-out scenario, offshore wind technology is expected to dramatically advance in the coming decades. This would allow for even larger generators, towers, and batteries for increased energy production. After the 25-year turbine lifetime, repowering would be very attractive. Chicago is positioned to become a major consumer of offshore wind energy, though this is outside the scope of this year's competition.

The Tesla Megapack battery energy storage system comes with a 15-year warranty to cover defects and failures, and an optional agreement can be made for 20-year capacity maintenance.[67] As lithium-ion capacity will degrade faster than the generation capacity of the wind project, the capacity maintenance agreement will be vital for supporting the future of the combined wind and battery projects.

3.0 Flaws and Environmental Analysis

3.1 Critical Habitats and Wildlife Analysis

The lease region is home to a high volume of ecological activity, requiring research on potential environmental impacts, legislation compliance, and mitigation techniques to offset ecological interference. Avian species of the area can be grouped into clades for generalization based on breeding, nesting, and foraging activities.[68] These clades include waterbirds, shorebirds, land birds, raptors, and gulls/terns. The two groups most susceptible to interactions with the wind turbines are waterbirds, which can forage up to 10 miles from shore, and gulls/terns that follow fishing boats indefinitely further from shore. Monitoring the activity for both clades will prove imperative in collision mitigation efforts.

The Great Lakes Region sits under the Atlantic and Mississippi Flyways, carrying over 300 species of migratory birds between Canadian breeding grounds and Central American wintering grounds.[69] The Western Great Lakes Bird and Bat Observatory counted roughly 175,000 and 200,000 seasonal migrants during the Fall and spring migration periods in 2017.[70] The region exists as a stopover habitat for these species, causing seasonal, cyclical avian population increases. spring migration season consists of migrants concentrated on the western and southern shores of Lake Michigan and Fall migration season brings species to the southern and eastern shores.[71] Accurate predictions of migratory movement over the Great Lakes themselves are underdeveloped, and current assessment studies rely on radar and acoustic recordings. Radar observation of bird migration showed nocturnally dense concentrations of migrants south of the proposed project area, but limitations in the experiment prevented the extrapolation of trajectories. Intensive studies predicting migratory flight patterns over Lake Michigan are a high priority. To better predict collision incidents, monitoring devices could be placed around the southern, eastern, and western shorelines as an early warning system during peak migration seasons.

Species protected by the Migratory Bird Treaty Act[72] travel through the flyways, and the potential increase in mortality of these species by the offshore wind project would require authorization by the Department of Interior U.S. Fish and Wildlife Service. Of the other residential species in the Great Lakes region, 53 are federally listed as threatened or endangered. Included in this list are the Piping Plover, the Indiana Bat, and the Northern Long-Eared Bat.[73] Development of the project requires compliance with recovery plans for these species and submission for permits outlined in the Endangered Species Act (ESA). Mitigation of take of listed species include seasonal turbine curtailment during periods of high migration, indicated by the preliminary environmental studies. Incidental Take permits would be necessary to acquire so that migratory and endangered species killed by wind project activities would not prevent the project from continuing.

Several marine species in the Great Lakes region also fall under ESA protections, and research related to potential degradation and destruction of habitats will prove beneficial. Mechanisms of prey and mate detection in the American Eel and Lake Sturgeon may be impacted by electromagnetic fields emitted from submarine transmission cables.[74] To mitigate interruption to these species, transmission cables should be woven in steel and potentially buried to reduce EMF impacts on marine species.

The Great Lakes coastal wetlands are recognized as an imperiled resource by the State of the Lake Ecosystems Conference under the U.S. Environmental Protection Agency (EPA). Also, the Great Lakes Water Quality Agreement between the United States and Canada, coordinated by the EPA, oversees invasive species prevention, protecting habitats, and improving water quality through Lake-Wide Action and Management Plans.[75] With the inclusion of both shoreline and marine foundational monitoring systems in the project, data collected can be shared with the Great Lakes Coastal Wetlands Consortium and the Great Lakes National Program Office to offset ecological impacts from development. The International Joint Commission was established by the United States and Canada under the Boundary Waters Treaty of 1909. This established a joint commission that oversaw the use of the Great Lakes, including when used for power generation and controlled quantity and quality levels of water. The Great Lakes Water Quality Agreement, amended most recently in 2012, between the United States and Canada, is an agreement to protect and restore the water quality levels of the Great Lakes.

3.2 Risks, Fatal Flaws, and Mitigation Strategies

While the project is far from the coast, making migratory bird collisions unlikely, there is still a chance these takes could happen. If proper mitigation actions are not adhered to, it is possible this project will not approved, making this a potential fatal flaw. To mitigate this, Incidental Take Permits would have to be acquired for the number of expected takes of migratory birds and endangered species per year. Since European countries have about a thirty-year head start on American offshore projects, many mitigation strategies can be learned from their experiences. Another way to prevent avian deaths is to paint the base of the tower and blade tips a different color than white, such as black.[76] This allows for a greater visual marker for avian species to avoid the area. Curtailing during high migration periods may also be a necessity to reduce collisions.

The Great Lakes have been referred to as freshwater inland seas because of their vast expanse. Because of this, it is common for tourism to center around the natural beauty of the lakes, causing the "Not in My Backyard" phenomenon to take place. To mitigate this, the project is placed far enough from the shore so that it will not be able to be viewed by lakegoers. The turbine's location will also not interfere with shipping traffic as they are spaced far enough apart to allow vessels to pass through uninterrupted. If petroleum products are spilled, such as hydraulic fluid or grease, oil skimmer trawl nets,[77] or oleophilic, hydrophobic, and magnetic (OHM) sponges[78] can be used on the water surface to prevent further contamination of the lake. These are commonly used methods on offshore oil derricks to prevent contamination and are reusable.

Lastly, the project can be conducted in soft starts, where construction is slowly ramped up to lessen the sudden impact loud noises can have on marine life. This will mitigate the environmental stress on native wildlife and decrease the chances of marine death or migration.

While a grid study is necessary for every project, renewable or not, they take approximately three years to complete and currently, there are two terawatts of energy projects already in the queue. This could significantly delay the start of the project. However, TWT believes that since a currently existing coal power plant will be taken over and the same infrastructure used, a grid study will be able to be expedited since much of the work has already been done. BESS also has shorter study times in MISO compared to wind or solar projects alone.

3.3 Green House Gas and Waste Reduction Estimate

To analyze the greenhouse gas emissions that will be avoided through this project, TWT will use emissions from the burning of coal. Even though the MISO grid is primarily powered by natural gas, and thus its emissions are the first instinct to use in this calculation, as renewable energy enters the grid coal power plants are shut down before natural gas power plants, as shown in the ERCOT grid.

Generating 1 MWh of electricity requires burning 1140 pounds of coal.[79] This produces gaseous emissions of 2,100 pounds of carbon dioxide, 3.9 pounds of sulfur dioxide, and 1.6 pounds of nitrogen oxides.[80] Of note is that the carbon dioxide emissions from coal are greater than the amount of coal originally input, this is due to the burned carbon reacting with the oxygen in the surrounding air. Burning coal leaves solid waste as well in the form of coal ash which contains radioactive thorium and uranium, as well as mercury. Emissions from the extraction and transportation of coal are impactful to the environment, however, they are outside of the scope of this analysis.

TWT's project has an estimated AEP of 6,961,700 MWh/yr; this leads to an estimated emissions savings per year of approximately 7,007,000 tons of carbon dioxide, 13,000 tons of sulfur dioxide, and 5,300 tons of nitrogen oxides. The carbon dioxide reduction from this project is equivalent to taking a third of gasoline cars in Wisconsin off the roads.[81][82] This is a considerable reduction in emissions in the face of anthropogenic climate change. Coal power plants have an average water withdrawal intensity of approximately 21,000 gallons of water per MWh.[83] Based on the project's AEP of approximately 6,961,700 MWh/yr, the project should save approximately 128 billion gallons of water per year.

3.4 Permitting

A barrier to this project is the unique permitting process inherent in developing an offshore wind project in Lake Michigan. Because multiple states border Lake Michigan, certain regulatory hurdles must be cleared in each one of those states, not just the state where the project is physically located.[84] The widespread regulatory approval that is needed for Great Lake development has led to ambiguity about what permitting needs to be done, potentially leading to increased costs and prolonged timelines.

TWT has identified 15 federal statutes from 13 federal agencies that require consideration and compliance. In addition, there are approximately 27 state statutes in Wisconsin. A full audit will need to be completed before construction to identify permits that will need to be completed from Lake Michigan border states Illinois, Indiana, and Michigan, or any state that may consider themselves stakeholders in the project.[85] This process speaks to the complexity that comes with permitting a wind project in the Great Lakes.

The lease area falls within areas of endangered species, approval from the BOEM will be needed in accordance with the Endangered Species Act and the Marine Mammal Protection Act of 1972. This requires a Habitat Conservation Plan (HCP). Under the BOEM Renewable Energy Program Regulations (30 CFR 585), Subpart H: once notified of the existence of endangered or threatened species in the vicinity of the lease, BOEM will consult with appropriate state and federal Fish and Wildlife agencies in the vicinity of the lease to identify whether, and under what conditions, the project may proceed. Under the Submerged Lands Boundary Act, the United States still retains the right to regulate offshore activities in the Great Lakes despite being inland, as the Great Lakes are considered “high seas” for the purposes of, in part, commerce regulation.

In Wisconsin, the state government prohibits local governments from blocking new wind projects unless a health or safety risk is posed to the public. All permitting authority over wind turbines in the state is under the authority of the Public Services Commission if the project is greater than 100 MW.[86] All other wind projects must be approved by the local government but must adhere to PSC wind siting criteria. This will alleviate some of the pain in the permitting process as it gives one central body in the state to work with it.

In the early history of Wisconsin, logging was a major source of industry, and logs were often sent down rivers and even the lake itself to deliver to mills. However, many logs sank or became stuck in lakebed mud. These logs are property of the state of Wisconsin and a permit must be obtained from the Board of Commissioners of Public Lands, the Wisconsin Department of Natural Resources, the Wisconsin State Historical Society, and the U.S. Army Corp of Engineers if a log is disturbed during construction activities so that it may be reclaimed by the state of Wisconsin, which would most likely occur during the installation of the collection system near the coast. A bond of $10,000 must be paid in addition to a $500 permit application fee.[87][88]

4.0 Financial Analysis

4.1 Market Conditions

Contextualizing this project within the wider grid is important in informing TWT’s decisions. This project takes place in the Midcontinent Independent System Operator grid. The average price of residential electricity in Wisconsin is 16.75 ¢/kWh; this is above the national average of 16.19 ¢/kWh.[89]

The Renewable Portfolio Standard (RPS) of Wisconsin was to generate 10% of all electricity from renewable sources by 2015.[90] Having met and exceeded this goal in 2013, Wisconsin now generates 11% of all electricity from renewable sources as of 2022, 30% of which comes from wind energy.[91] TWT’s proposed project would contribute to a doubling of Wisconsin’s renewable energy generation. In 2019, a state executive order set a goal that 100% of all electricity consumed in Wisconsin would come from carbon-free sources by 2050.[92]

Increasing costs of raw goods, labor, and materials, as well as high interest rates, are important to factor into financial calculations. These complications have, in the last 2 years, put a damper on the United States' offshore wind goals. Recent developments have shown revitalization in those goals, with companies like BP and Orsted recommitting to wind projects, at a renegotiated higher sale price of energy produced.[93] These factors will influence the design of the project. To monitor potential future prices, TWT will look at the Producer Price Inflation (PPI) to understand how the cost of goods related to production will increase during construction and through the lifetime of the project. Since the beginning of 2023, PPI has returned to normal levels,[94] after spiking to the highest levels since 2010 after the COVID-19 pandemic. Federal interest rates are currently 5.33%. Current projections show that interest rates have peaked, though it is currently unclear if rates will return to pre-pandemic levels.[95]

The cost of a grid interconnection study in MISO includes a $7,000 flat fee with an additional $8,000/MW,[96] meaning the study would add approximately $14,744,000 to the total budget. Studies have also indicated that in addition to the cost of the grid interconnection study, MISO can require additional upgrades to transmission lines upon review before a project is fully approved, meaning the total cost of this project could be even higher.[97] 24% of projects that submit an interconnect study in MISO reach the commercial phase.[98]

Wisconsin has a flat 7.9% corporate income tax[99] and private power companies are required to pay 1.59% of the gross revenues made from the sale of electricity for resale. The City of Oak Creek, where this project will be taxed from, has five tax districts:[100, 101] Milwaukee County, Oak Creek/Franklin School District, Milwaukee Metro Sewerage District (MMSD), Milwaukee Area Technical College (MATC), and the City of Oak Creek. Per $1,000, 4.51₵ will go to Milwaukee County, 1.3₵ will go to MMSD, 5.80₵ will go to the City of Oak Creek, 8.16₵ will go to Oak Creek/Franklin School District, and 0.85₵ to MATC.[102] All of these taxes decreased from 2022 to 2023, with a total decrease of 1.21%.[103,104] There is a First Dollar Credit of 72.53. These taxes will only apply to the POI as further described in 4.2 Incentives.

Orsted, the world's largest developer of offshore wind energy, canceled Ocean Wind 1 and 2 which would have provided over 2,200 MW of electricity to New Jersey due in large part to high inflation and interest rates, supply-chain issues, and permitting delays.[105] These will all be challenges that must be overcome by TWT for the project to be successful.

4.2 Incentives

Wind energy projects have access to several federal incentives that are meant to support wind industry growth by increasing revenue and reducing the risk associated with constructing and operating a wind project. The Production Tax Credit (PTC), which was extended in the bipartisan Inflation Reduction Act of 2022, gives operators a 2.6 cent tax credit per kWh of energy produced. The PTC is eligible for stackable 10% bonus credits per kWh produced for meeting domestic manufacturing thresholds, and for locating facilities in fossil-fuel-dependent "energy communities". This tax credit is available for 10 years after the beginning of operations. In the event of a potential repowering situation, the PTC can be earned again, meaning that if the project installs new generators the PTC can continue to be earned for another ten years.[106]

The Business Energy Investment Tax Credit (ITC) is a dollar-for-dollar tax credit of 6% or 30% of the cost of installed equipment. 6% is the base amount of the ITC and to reach 30% the project must meet apprenticeship and prevailing wage requirements. The ITC, like the PTC, is eligible for stackable bonus credits of an additional 10% each for meeting domestic manufacturing thresholds and for locating facilities in fossil-fuel-dependent "energy communities", bringing the total possible ITC to 50%.[106]

Renewable Energy Certificates (RECs) are a market-based incentive that is used to represent the non-power, environmental, and social benefits of renewable energy. One REC is given per MWh of electricity generated.[107] As with most wind energy developments, the project will be in debt initially after construction and the beginning of operations. This means that nonrefundable tax credits, such as RECs, cannot be used until the project is cash flow positive, and the loan is paid in full. Until that time comes, there is an alternative use to RECs that can be used to increase revenue for the project. REC arbitrage allows for generated RECs to be sold to third parties, who buy RECs to substantiate carbon footprint reduction claims. An agreement can be made to sell all RECs generated to a single buyer for a fixed price, or RECs can be put in the wider market to be sold at a variable price. The price of a REC on the open market has been rising, from $1 per REC to nearly $8 per Green-e® Certified REC. REC arbitrage will be an important revenue source for this project.[108]

Wisconsin gives electric generators in the state the option of using Renewable Resource Credits (RRCs) to satisfy their RPS requirements.[110] As this project generates renewable energy, it will be eligible to create an RRC able to be sold for each MWh of electricity generated in excess of the project's RPS requirement each year. These RRCs can be sold to other electricity generators in the state, coal or natural gas plants ideally, to be used to meet those plants' RPS requirements.[110] RRCs are another source of revenue for this project.

The Wisconsin Department of Revenue passed an exemption from general property taxes, though this would only apply to the wind turbine lease area and battery lease area themselves as equipment and components that are part of conventional energy systems, such as the POI, are excluded.[111] The Environmental Protection Agency provides Brownfields Cleanup Grants of up to $2 million for sites contaminated by hazardous materials,[112][113] such as the POI TWT proposes to acquire, though $500,000 is the most common grant awarded. It is expected that the total cleanup process will cost approximately $600,000.

The ITC and PTC cannot be claimed by a project at the same time, therefore financial simulations must be run to determine which would lead to the most profit from this project. Speaking generally, the ITC is good for projects with a large upfront cost that are on the cusp of profitability due to substandard generation, the PTC is good for projects that generate lots of electricity. As this project is projected to generate 6,961,700 MWh/yr, financial simulations show that the PTC should be used to maximize profit. A partnership with a local non-profit tax-exempt organization will be needed to monetize the tax credit earned from the PTC.

4.3 Capital Expenditures

Due to the inability to acquire live prices of physical units, coupled with the variability in the price of raw materials both in time and in the market, mathematical approximations were used in financial calculations for portions of this report. Components of Capital Expenditures (CAPEX) such as turbine, substation, cabling, and substructure unit costs were approximated utilizing formulas and reasonable information. These units have variable costs associated with site-specific features such as water depth, distance to shore, capacity, and unit design. This approach increases CAPEX accuracy influenced by environmental aspects and design decisions of the project. NREL's System Advisory Model (SAM)[114] has been utilized to aid in estimating these costs as well as organizing information. These are the costs estimated for TWT's 1.1GW project of fifty turbines, in the designed layout.

The rating of the chosen turbine is 22 MW, using a price provided by SAM of $1,405.80/kW, the total cost of all the turbines is estimated to be $1,545,500,000. This is in line with the cost expected.

For the balance of systems costs, which include the collection system, port infrastructure, foundations, development, and miscellaneous charges but excludes the cost of the turbines, SAM estimates these costs to be $382,500,000 total, a cost of $347/kW. The HVDC-to-shore line will cost approximately $337.5 million alone based on the HVDC Caithness-Moray line in Scotland.

Based on Tesla's specifications for the megapack, the price for a battery in 2024 will most likely be approximately $282/kWh. With a storage capacity of 2,972.2 MWh, this brings the estimated cost of the battery system to $961,079,920, including installation.[115] However, as the battery meets the eligibility standards for the 50% ITC outlined in section 4.2, the net cost will be just $480,539,960 after the refundable tax credit.

This brings the total installed cost of the project to $2,408,663,960 including sales tax, installation, and all the necessary and appropriate contingencies. All assets will be depreciated using the 5-year Modified Accelerated Cost Recovery System (MACRS)[116] that is offered to wind and battery projects. This system helps renewable energy projects increase bankability and profitability by reducing the time it takes to depreciate a project's assets from 20 to 5 years.

4.4 Annual Operating Costs

Wisconsin has generally favorable renewable energy policies, though some may be a double-edged sword in terms of financing. All electric utilities are required to pay 1.2% of their annual operating revenue from sales of energy to fund statewide energy efficiency and renewable resource programs.[117]

The Port of Milwaukee has an average cost of $25,000/acre, making the annual port rent around $150,000 when including other fees associated with equipment and permits.[118] Annual operating costs for the wind project are estimated by SAM to be $40/kW per year,[119] $44 million per year. Likewise, Tesla estimates that $3,950,000 will be spent annually on battery maintenance,[120] with a 2% annual escalation rate.

The insurance rate for this project is set at 1% of the total installed cost annually. This is slightly lower than the 2-3% that is standard in the wind industry[121] due to the lower failure rate of direct drive turbines that generate power without a gearbox. The absence of a gearbox means that this project will not suffer from costly and lengthy downtimes associated with gearbox repairs.

4.5 Pro Forma

To reach an NPV of $0 in 20 years, the breakeven Power Purchase Agreement (PPA) price is 1.23 ¢/kWh with an escalation of 2.5% every year, which is standard within the industry. Due to inflationary pressures, the escalation rate could be even higher year-over-year. There is a large delta between the breakeven PPA price and the average price of electricity in Wisconsin of 11.95 ¢/kWh. The Biden-Harris administration announced the new Offshore Floating Wind Shot,[122] this sets the target energy price for floating wind to 4.5 ¢/kWh, to meet this goal TWT's project will sell energy produced for 4.0 ¢/kWh, exceeding the goal of the Biden-Harris administration, and ensuring a strong return for investors. The BESS will sell energy at the same price, ensuring a steady supply of cheap energy for Wisconsin, and a steady income for the project.

Metric	Value
Annual AC energy in Year 1	6,961,700,000 kWh
Capacity	1,100,000 kW
Capacity factor in Year 1	69.8%
PPA price in Year 1	4.00 ¢/kWh
PPA price escalation	2.50 %/year
LPPA Levelized PPA price nominal	4.92 ¢/kWh
LPPA Levelized PPA price real	3.90 ¢/kWh
LCOE Levelized cost of energy nominal	1.84 ¢/kWh
LCOE Levelized cost of energy real	1.46 ¢/kWh
NPV Net present value	$2,022,154,624
IRR Internal rate of return	37.39 %
Year IRR is achieved	20
IRR at end of project	37.43 %
Net capital cost	$2,080,715,136
Equity	$1,040,551,552
Size of debt	$1,040,163,520

Table 1 – SAM Pro Forma Table

Internal Rate of Return (IRR) is used to estimate the profitability of a project and to understand the return associated with the risk of an investment. After all, this project's main goal is to generate renewable energy such that it generates monetary returns for its shareholders. Using a PPA price of 4.0 ¢/kWh, SAM estimates that the IRR at the end of this project is 37.43%, with a total lifetime revenue of $6,776,000,000.00.

The DSCR describes the ratio of debt to equity over a project. The DSCR TWT has decided on is 50%. This value was decided upon from research and talks with industry professionals. To reach a 50-50 equity-debt split, TWT will be using an equity partner. The sale of RECs and RRCs can be used to further encourage this partnership.

Real Levelized Cost of Energy (RLCOE) measures the lifetime cost of a project divided by energy production. The RLCOE for TWT's project is 1.46 ¢/kWh. LCOE for new offshore wind projects has increased from 2021-2022 by 2%, to 7.9 ¢/kWh.[123] TWT's project lands well below this mark due to the extremely high AEP and capacity factor of the chosen turbine in the site.

Financial models were run throughout the entire course of this report. During this time, the breakeven PPA price fluctuated both up and down as financial and technical aspects were iterated on, becoming more accurate as the project reached its final stages. This modeling approach is used to better match real-world expectations.

4.6 Auction Bid

TWT's auction bid price was based on research of every offshore lease block that has been sold in the United States so far, about thirty-one leases,[124] with some mergers and segregations altering the number of wind projects that will be built. Based on historical lease data, the California Offshore Wind Auction was chosen as the primary basis for TWT's bid price in Lake Michigan. These leases were chosen because they are most similar to Lake Michigan in terms of the deep bathymetry requiring floating foundations and the high, consistent wind speeds. Prices ranged from $2,503/acre in the northern lease blocks to $1,765/acre in the southern lease blocks. This difference mainly comes from the lease block's size, as the northern blocks are about 20% smaller than the southern blocks and the bathymetry/wind speeds are only slightly different.[125] Based on this analysis, TWT is prepared to spend $3,000/acre for 32,500 acres or $97.5 million total, with a maximum bid price of $130 million.

5.0 Optimization Process

During the technical analysis of the project TWT paid close attention to the cascading effects that one decision can have on other aspects of the project. For example, increasing turbine spacing within rows decreases wake losses, leading to increased production. However, this also leads to an increased balance of systems costs and electrical losses in the collection system. To solve this and other optimization problems, TWT ran financial and technical simulations to find a balance between many interacting factors.

The BESS was developed to cover the 16% wind energy forecasting error. 2,925 MWh of battery storage will cover this error as well as cover the two, four-hour peak energy demands during the day, maximizing energy output, grid stability, and profits. By using the four-hour discharge option of 743 MW, transmission constraints are minimized versus the two-hour 1,463 MW discharge option.

The charge/discharge cycle of the BESS was designed with demand data from the MISO region provided by the US Energy Information Administration. This data included 5 years of data with a temporal resolution of 1 hour that was averaged together and broken down by month to design charge/discharge cycles on a month-by-month basis. This process increases profitability and reduces instances of production-demand mismatch that may lead to a curtailment event.

One of the best ways to optimize the profitability of the project is to perform maintenance and repairs during the low wind speed summer months as often as possible. SAM simulations were conducted in tandem with monthly wind speed analysis to minimize lost production due to turbine maintenance.

Deicing technologies are relatively inexpensive and can significantly prolong energy production in the winter when wind speeds are highest. By spending roughly $50,000 to install deicing equipment per turbine, profits will be significantly increased.

Conclusion

A preliminary site assessment was completed in Lake Michigan and Lake Superior, determining that Lake Michigan is the superior choice for a wind project, due to a variety of geographic, infrastructural, and financial reasons. Lake Michigan has an average wind speed of 9.7 m/s at 140m, the IEA 22 MW Reference turbine was paired with a tension-leg platform floating foundation to produce an AEP of 6,961,700 MWh/yr; from a 1.1 MW nameplate capacity wind project and a capacity factor of 69% along with a BESS. There are few environmental concerns, with the biggest being the endangered species in the area. With a PPA of 4.0 ¢/kWh and an RLCOE of 1.46 ¢/kWh, this project will be significantly cheaper than other energy options in the area. TWT is willing to bid a maximum of $3,000/acre for 32,500 acres, a total of $97.5 million. This project is an incredible opportunity to showcase the potential of wind energy in the Great Lakes and provide an excellent return on investment.

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1.1 Site Selection

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