RICE WIND ENERGY

Rice University 2023–2024 Project Development Final Report

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1.0 Executive Summary

Rice Wind Energy Corporation presents this proposal for a 450 MW wind farm located on Lake Michigan, about 10 KM off the coast of Ludington, MI. The project will consist of 30 x 15 MW Vestas V236-15.0 turbines, oriented in a 3 x 10 configuration. RWE analyzed multiple possible locations and determined that this area on the eastern part of the lake offered the best combination of wind resources, accessibility, environmental conditions, and interconnection possibilities. Financial modeling was performed using NREL's System Advisor Model, while Solute's FUROW was used for site layout computation and visualization. RWE plans to sell the energy generated by the project at an initial PPA price of $87.4/MWh to Consumers Energy of Michigan as part of an initiative to both reduce dependence on fossil fuels and reduce statewide energy costs. The project will generate 1.7 million MWh of energy per year, achieving an industry leading 42.7% capacity factor.

2.0 Site Description

After analyzing multiple locations across all five great lakes, the team has selected to build the wind farm on Lake Michigan. Based on wind data at turbine hub height, Lake Huron and Lake Erie performed the worst. This fact alone took them out of consideration for the location of the farm because as per the wind profile power law relationship, wind speed is a major factor in how much power the farm produces. For Lake Superior, the lack of installation infrastructure and interconnection site capacity surrounding the lake made it less compatible with wind farm placement [1]. Lake Ontario was the second choice for the location of the wind farm. However, it was taken out of consideration largely because Ontario has a large bird population, is in the direct flight path of multiple migratory birds, and is smaller than other lakes. Therefore, Lake Michigan with its high wind speed, developed infrastructure and smaller bird population quickly made it the forerunner for the farm's location. Specifically, the wind farm will be on the east side of Lake Michigan, southeast of Ludington, inside of the black rectangle as seen in Figure 1. The rectangle has a width of 6.10 km and a length of 16.4 km. The specific site characteristics of the location and further reasoning for choosing it will be explained in terms of each component below.

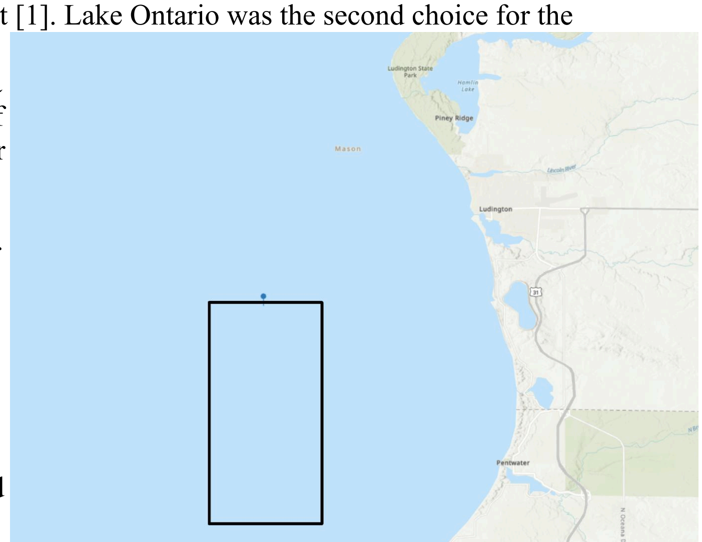

Figure 1: Wind Farm Location

2.1 Site Characteristics

No singular location has the ideal conditions for every metric —the location selected provides the best balance between turbine energy output, interconnection site proximity, effects on wildlife, local resident appeal, and activities on the lake.

<u>Bathymetry:</u>
Based on ArcGIS data, the bathymetry of the Great Lakes varies extensively from lake to lake [2]. When looking at a bathymetry map the goal was to find a large area away from the shore that is relatively flat with little to no geographic anomalies on the lake floor that might affect the installed foundations. Also, to eliminate the use of fixed foundations, a depth between 60 and 300 m is required [3]. The site chosen in Lake Michigan meets all of the requirements stated above with a depth of 60 m.

<u>Freezing of the Great Lakes:</u>
Wind energy development in the Great Lakes Region poses the unique challenge of freshwater freezing conditions. There is no location amongst the Great Lakes that has not frozen over in the last 10 years. That being said, Lake Michigan in the last 10 years has had a lower percentage of its surface freeze over

every year than compared to Lake Superior and Lake Huron. The wind farm has to be able to withstand ice and the movement that it causes. By choosing a location that freezes over less, it will also reduce structural deterioration. Therefore, the frequency and intensity at which a location on Lake Michigan freezes over every year was taken into account. At the chosen location in the last 10 years, it has frozen over to some percentage 4 times [4].

<u>Wave Height:</u>
An examination of The NOAA's data on wave height – which was extracted by Buoy 450024 the closest buoy to the wind farm located 6.85 miles away – reveals a low of 0.0 m throughout the year and a high of 2.97 m [5]. The selected site has an approximate average wave height of 0.64 m. Wave height influences the atmosphere tens of meters up (approximately 100 m) into the swept area of turbines. The dynamical roughness of waves – which can be modeled by simulations such as WIWiTS – can be shown to produce different results on turbines in various cases, such as if the wind is aligned with a swell, wind opposes a swell, or wind over a smooth surface of low waves [6]. Selecting an area with a lower average wave height is important in the longevity of the turbines and it will result in more consistent power generation. The smaller the waves, the less disruption they will cause to the atmosphere near the blades, and the less likely the power generation is to be lower than expected.

2.2 Wind Resource Assessment
The RWE team utilized The World Bank Group's Global Wind Atlas to get an overview of the wind capabilities of the Great Lakes [7]. The data was taken at an altitude of 150 m above sea level – influenced by the turbine's hub height. The Atlas supplied mean wind speeds and mean power density. Although both data sources were deeply considered, the mean power density data was prioritized due to its focus on indicating better wind resources rather than wind speed alone. Despite this choice, it should be noted that mean wind speed and mean power density are, for the most part, directly proportional.

It was found that Lake Erie and Lake Ontario exhibited mean wind speeds of approximately 9.18 ± 0.12 m/s and 9.01 ± 0.20 m/s respectively at 150 m above sea level. That being said, it was found that Lake Ontario's mean wind speeds near developed areas and possible interconnection sites – near Syracuse, NY for example – reach 9.34 m/s. Lake Huron exhibits similar conditions; however, higher wind speeds are found much further into the lake and cross over into Canadian territory. Lake Superior experiences significant mean wind speeds of approximately 9.55 m/s near Munising, MI and Marquette, MI, yet power cannot effectively be extracted in these locations due to infrastructural obstacles. The northern mass of Lake Michigan exhibits mean wind speeds of about 9.68 m/s. Although mean wind speeds as high as 9.74 m/s can be experienced further into the lake. NREL categorizes floating offshore wind resources in classes ranging from Class 8 to Class 14. Accordingly, the available wind resource lands just past the lower bound of Class 11—wind speeds ranging between 9.6 m/s and 10.01 m/s [8].

Building upon the findings from The Global Wind Atlas, NREL's System Advisor Model (SAM) was used in combination with the NREL Wind Toolkit to further assess the efficacy of each potential location at 140m, the finalized hub height of the turbines [9]. Holding farm layout, turbine selection, and all parameters except geographical location constant, multiple simulations were performed at various sites across all five lakes. The results from this analysis confirmed that Lake Huron and Lake Erie would not be good locations for the wind farm. The simulations on these two lakes performed 15-25% worse in terms of simulated capacity factor and yearly energy output. Again Lake Superior exhibited superlative performance metrics. As for Lake Ontario and Lake Michigan, SAM simulations again corroborated RWE's existing expectations, as the mean capacity factor across various feasible locations was found to be remarkably similar – just 2.73% in Lake Michigan's favor.

Overall, the wind resource assessment points to the conclusion that the project should be located on Lake Ontario or Lake Michigan. Lake Michigan was selected over Lake Ontario for reasons previously mentioned in the report. The exact location of the project exhibits mean wind speeds of 9.58 m/s. The process of choosing the exact location on Lake Michigan can be found in section 3.8 of the report.

2.3 Impact Mitigation

Environmental:

In the choosing of the site location, lake and biodiversity preservation remained at the forefront of the decision-making process with an emphasis on the infrastructure's long-term environmental impact. The comprehensive assessment conducted focused on minimizing potential impacts on wildlife, examining three crucial factors: bird and bat flight patterns, aquatic life, and overall environmental health. To minimize risks to various aviary species, the wind farm location was selected to avoid key bird migration corridors (particularly the Atlantic and Mississippi flyways), endangered bird habitats and sanctuaries, areas of American Bird Conservancy (ABC) Red WatchList bird habitats (which have particular habitat requirements and/or are vulnerable to harm from wind turbines), and areas the Endangered Species Act has designated as critical. Due to the Michigan shoreline's importance to migratory birds, The National Audubon Society recommends that protective measures are implemented [10]. For example, research shows that painting turbine blades black significantly increases blade visibility to birds, resulting in a 70% reduction in bird collisions [13]. Additionally, an analysis of ABC's Wind Risk Assessment Map reveals that wind energy development over the chosen area does not drastically interfere with vulnerable bird species [11]. The site location along the southern Michigan coast strategically dodges areas of high vulnerability further north.

Bat species mortality rate minimization is an especially crucial factor in ensuring project sustainability. Research by NRG Systems shows that bats (especially tree-roosting bat species) are attracted to turbines, causing increased bat activity within the turbine's rotor-swept area and therefore increased mortality [13]. Research supports the notion that bat deaths occur most at lower wind speeds; low wind speed curtailment may be implemented to slow turbines down during times of weak winds (< 5 m/s) – potentially preventing 50.0% of bat fatalities [14]. This method of mitigation is effective yet economically ineffective due to reduced power generation. Per NRG Systems, an ultrasonic acoustic bat deterrent system would be implemented in tandem to minimize bat species mortality by emitting high-frequency pulses that jam bat species' echolocation [14]. A study of Illinois bat species' interactions with these mitigation strategies shows that in total, about 67% of bat fatalities were prevented when implementing both a 5 m/s curtailment and eight bat deterrent units (BDUs). To minimize the financial loss incurred by the curtailment, the curtailment speed may be reduced to 3 m/s [14].

Additionally, fish spawning and habitat locations were investigated to avoid key locations with existing large populations along the shore. Most crucially, the ideal spawning habitats for Lake Trout, which is populous across the Great Lakes, as well as areas where the Lake Sturgeon, which is endangered across the Great Lakes, is abundant were successfully avoided [16,10]. To mitigate the fact that the proposed site is off a coast of moderate to high stress due to the high recreational activity in Ludington, an adaptive management program would need to be in place to track potential risks over time and prevent further anthropogenic stress from the site interactions [15]. Through monitoring, unforeseen challenges could be identified and farm functions could be adjusted as needed, adequately preparing data necessary for a low impact decommissioning and restoration operation at the end of the project life. The assessment also prioritized areas vital for maintaining Lake Michigan's biodiversity, ensuring non-interference with neighboring grasslands and protected lakeshores critical for environmental conservation efforts. By considering the needs of all life residing in the region, an attentive protection strategy can be implemented, respecting the diverse wildlife and natural ecosystem of the Great Lakes region throughout site selection and future construction processes.

Lake Activities and Local Impact:

The Great Lakes are heavily used both recreationally and for economic purposes. Lake Michigan is no exception to this. Therefore, the placement of the wind farm in a location that would least disturb the daily functioning of Lake Michigan as a whole was prioritized. RWE also emphasized lessening the impact the wind farm will have on the surrounding community of Ludington.

In terms of disrupting the economy or other industries, the wind farm's positioning ensures no adverse effects on port sites, including Port Milwaukee, and doesn't interfere with established freighter routes or boating highways [17]. Additionally, the location is not in any military training-restricted zones or FAA-restricted zones. There is also no ceiling at the proposed location, meaning it doesn't have a maximum height restriction because of air traffic, allowing the team to install the proposed wind turbines [18]. In terms of disrupting recreational activities, the wind farm is strategically located 12.7 km off the coast which avoids typical recreational boating routes and fishing areas, which are active year-round, preventing disruption to activities [19]. Also, Lake Michigan follows water sports guidelines prioritizing environmental protection and safety. Activities, typically concentrated near the shoreline, fishing and boating, must adhere to a 100-foot distance from objects in the water, preventing interference with proposed wind turbines[20]. Lastly, the overall size of the wind farm takes up a small percentage of the lake's surface area, therefore it is less likely to disturb activities as a whole.

The town of Ludington is known for recreational tourism and manufacturing factories, specifically Whitehall industries which support the automotive industry [21]. The location of the farm is south of the town's center and their recreational marina. The farm will in the short term bring an influx of jobs and investments into the town. This aligns with the town's master plan which states its priority to diversify its industries [22]. The project will overall pump money into the town which will also allow it to invest more into entrepreneurship, a key part of diversifying their industries. More concerns develop when analyzing the long-term effects of the farm. Since a major industry of the town is tourism, how the farm affects people's views could seriously impact money coming into the town. That being said the location of the farm is off of the town center and the major recreational areas including the marina and park. Additionally, the farm is 12.7 km from the shore. When the height of the turbines is taken into account, the farm will take up only a small portion of the horizon. This statement is based on a visual analysis done on a similarly sized and distanced from the coast project named Thanet off of the UK [23]. Overall, the location of the wind farm reduces its visual impact as much as possible. And, considering there is already a 56-turbine wind farm outside of Ludington, it is safe to assume the people in this community and those vacationing there are used to seeing wind turbines more than other communities [24].

2.4 Turbine Selection

The team analyzed turbine models based on the selected site's wind data and logistical concerns imposed by supply chain and construction limitations. As the proposed location features primarily class 11 wind speeds, the availability of wind resources did not play a significant role in the team's decision-making. Focus was placed on choosing the turbine that would most effectively capture these high wind speeds, i.e. a turbine with greater rotor diameter and high capacity factor. Instead, logistical constraints proved to be the major determining factor throughout the turbine selection process. Due to strict vessel size restrictions along the St. Lawrence Seaway (233.5 m length, 24.4 m width, 9.1 m draught), traditional offshore wind installation vessels such as WTIVs or even most Jack-up types cannot enter the Great Lakes [25]. Even if a smaller jack-up vessel were to be used, this would limit turbine selection to the 4-6 MW nameplate capacity range, as 12-15 MW heavy lift turbine installation vessels cannot be used unless fully assembled on the Lakes. However, another viable assembly option lies in assembling the floating substructure of the turbine at the port, and then towing the completed structure out to the site, a technique successfully implemented in projects such as the 2021 TetraSpar Demonstration Project in Norway [26]. Using this method, the turbine and foundation assembly can be completed using land-based equipment, removing any size constraints on turbine size.

To finalize turbine selection, performance benchmarking on over ten turbine models ranging from 6-15 MW was conducted using NREL's System Advisor Model (SAM). With farm location and a 50-turbine testing layout held constant, each model was evaluated according to its simulated capacity factor (%) and maximum annual energy output (kWh). These two metrics provide insight into both the operating efficiency and peak capabilities of the farm, painting a clear picture of turbine performance. Simulation results are displayed in Figure 2 (change when settled) below.

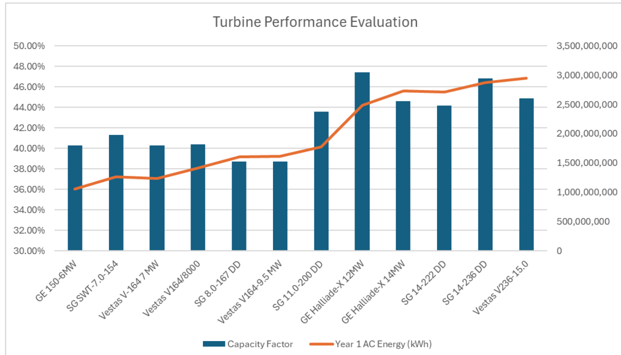

Figure 2: Turbine Performance Benchmarking

Additional factors considered in the turbine selection process centered around feasibility, supply chain, and historical trends in offshore turbine size. The plot below, taken from NREL's 2023 Offshore Wind Market Report, displays the global weighted average capacity, hub height, and rotor diameter of turbines in projects commissioned or set to be commissioned between 2012 and 2027 [27].

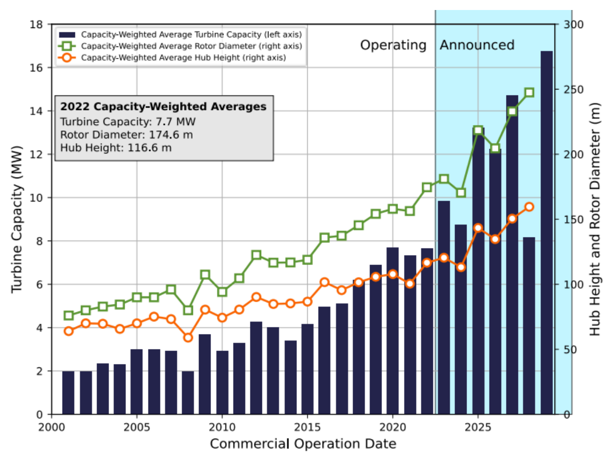

Figure 3: Historical Trends in Offshore Wind Turbine Nameplate Capacity,

As indicated by Figure 3 above, the size of offshore wind turbines has been steadily increasing since the turn of the century, with contemporary projects already utilizing turbines in the 10-15 MW range. It is predicted that these trends will continue at least into the 2030s, as major turbine manufacturers are already researching and developing platforms upwards of 18 MW [28, 27]. In order to remain competitive with the market moving forward, the turbine selection was narrowed down to the 12-15 MW range. GE's Haliade-X, whilst the most efficient and industrially proven of the five turbines that RWE tested in this output range, has little to no precedent in floating applications due to its immensely heavy nacelle—over 150 tons heavier than similar offerings from Siemens and Vestas [29]. Between the three remaining turbines, the team elected to pursue the Vestas V236-15.0. On top of having the largest nameplate capacity and annual energy output of all turbines that were tested, the V236 features an extremely modular design, with component dimensions designed to adhere to international logistical standards for shipping, road, and rail [30]. Given the size of the proposed farm, this modularity will play a critical role in reducing the balance of system costs. Further discussion on the turbine supply chain can be found in section 3.4 below.

2.5 Foundation

The analysis of foundation requirements was driven by two primary factors: the water depth at the farm site and the nature of the turbine assembly process. As stated in the bathymetry section above, the proposed location off the coast of Ludington features water depths of around 60 m. At these depths, fixed-bottom foundations become increasingly uneconomic, as the fabrication, transport, and installation costs of such large structures would be enormous [48]. On the flip side, this depth is far too shallow to accommodate Spar floating foundations, which due to their tall, cylindrical hull structure require water depths over 100m [49]. With these depth considerations in mind, the proposed turbine installation method of assembling the complete structure at port further reduces viable foundation types to only those that can be tug-towed from dockside to site. Two floating foundation types that satisfy these requirements were identified: Semi-Submersible foundations and Tension Leg Platform (TLP) foundations. While both exhibit various strengths and weaknesses, research suggests that the overall Technology Readiness Level (TRL) of TLP-type foundations is noticeably inferior to that of semi-submersible. Due to their high structural rigidity, TLP foundations struggle to cope with high-frequency dynamic loads, leading to unwanted pitching, heaving, and fatigue [49]. This, coupled with TLP's more expensive mooring system, motivated RWE's decision to opt for a semi-submersible foundation. While less laterally stable, semi-submersible foundations are highly buoyant—capable of supporting large turbines such as the selected Vestas V236—and feature simpler installation and mooring systems, making them the economically sensible choice of the pair [49]. Development of semi-submersibles capable of supporting current and future offshore turbines in the 15+ MW range is already underway, with projects such as Oceanwind's *Deepsea Star* reportedly nearing completion in the mid-2020s. Each semi-submersible foundation will be anchored using three suction anchors. Although the installation of suction anchors is more expensive than a drag-embedded system, suction anchors are more effective at distributing vertical loads, a necessary characteristic given the immense size of the V236 [50].

To protect the foundation from ice chunk collisions in the event Lake Michigan freezes over, the plan includes an installation of ice cones at the base of each structure. As ice sheets collide with the foundation, they will be broken apart by the ice cones, mitigating unwanted damage and fatigue to the turbine and substructure [51].

2.6 Detailed Layout

The layout was impacted primarily by the size constraints of the farm imposed by freighter highways located on all four sides. Allowing for at least 1 km between the freighter highways and the area affected by each turbine, an area of 15,914 acres was left. Using furrow for visualization and SAM for calculations, it was determined that a configuration would fit in the designated area with the lowest wake effect and highest capacity factor. This information led to a final layout design of 3x10 with a separation of 5 rotor diameters. Additionally, the middle row is offset by 2.5 rotor diameters, and the farm is angled at a tilt of 10 degrees. This configuration takes up an area of 14,864 acres with wake effect losses of 11.8397% and a capacity factor of 43.4263%.

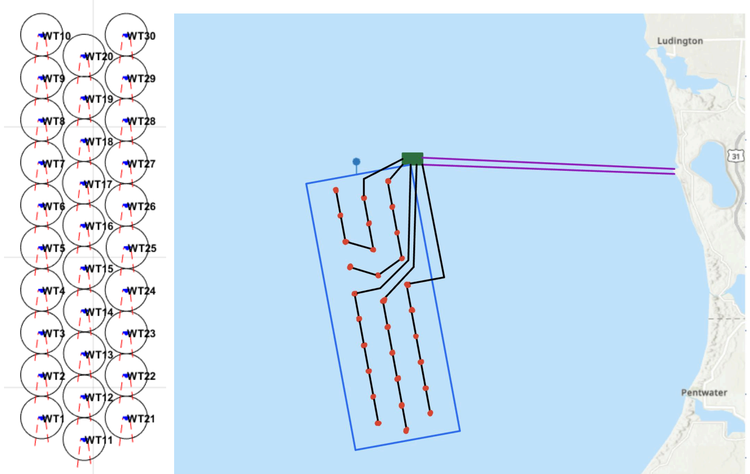

Figure 4: Layout of Turbines and farm Cabling

2.7 Transmission

The interconnection site played a large role in the final decision for the exact location of the wind farm. Choosing a location that would not need significant upgrades to allow the wind farm to integrate into the grid and that would be close to the project, will in the long run save money. One of the largest substations on the west coast of Michigan is located directly on the shore and near an area for high wind. The substation is located off of the Ludington Pumped storage plant, with the substation and the transmission lines having a capacity of 345 kV it would serve as a favorable interconnection point for the farm's transmission. It would also allow for easy access to the larger Michigan power grid. The substation currently supports the Ludington Pumped Storage plant which has the capacity of 1872 MW. The plant was built in 1969 to help stabilize the energy grid after the D.C. Cook Nuclear Power Plant, Palisades Nuclear Power Plant, and other coal plants were installed. The plant already works in tandem with nearby wind farms and solar farms, meaning the project also has the capacity to work with this existing storage solution. The state of Michigan is currently planning to close its remaining coal plants by 2025, the wind farm proposed would act as a replacement for the decommissioned coal plants therefore allowing for the pumped storage plant to be utilized to its full capacity [52].

In order to minimize cable distance and stay within the capacity of the selected cables, the cabling layout in Figure 4 was selected. It will utilize HVAC Array cables of 66 kV to connect the wind turbines to the offshore substation. These cables have a max capacity of 90 MW therefore each of the 5 cables shown connects 6 turbines [53]. The substation, the green rectangle in Figure 4, will step up the voltage to 132 kV. This will connect the array cables to the HVAC Export cables of 132 kV. There will be two export cables that will have a combined capacity of 700 MW [54]. This will be more than enough for the 450 MW project. To lower the risk of energy loss in transport, all of the cables will be at least 120 ft from each other, the two export cables will run 10.5 km to shore to connect with the Ludington Pumped Storage Plant substation, with its 345 kV transmission lines, located directly on the coast.

2.8 Hybrid solution

After an in-depth analysis of the needs and current infrastructure of the proposed interconnection site, the optimal and most dependable choice for a hybrid solution would be an energy storage solution. However, there is a lack of sufficient space around the intersection site for new large storage units to sufficiently stabilize the grid. For reference, a 120 MWh containerized lithium-ion Battery Energy Storage System for a solar farm in Hawaii consists of 26 shipping containers [31]. Also, with site proximity to the Ludington Pump Plant, which acts as a large battery and has a capacity of 1,872 MW, any storage installation would be minuscule compared to the plant [32,33]. And, as mentioned earlier in the report, with the closing of coal plants in the next few years, there will be available capacity for the project to utilize the Ludington

Pump Plant to help with farm integration into the grid. This option would be the lowest risk as the system is already maintained and equipped for large energy loads and features a feasible connecting site at the plant substation.

Green hydrogen feasibility was also considered in depth due to movements toward hydrogen infrastructure, including production sites near industrial areas and fueling hubs in Michigan [34]. However, green hydrogen production was ultimately not chosen because of substantial costs associated with the electrolyzer, storage, and transportation with little payback potential, at least within the next 25 years [35]. It was most feasible to derive 50MW of the wind farm's electricity output for the electrolyzer. Assuming the wind farm allows the 50MW electrolyzer to run at high load factors and full load hours to minimize the unit production cost of hydrogen, 2,340 tons per annum (TPA) of green hydrogen gets produced, and 55.4kWh of electricity is consumed for every kilogram of hydrogen produced [36,37].

It was decided that the compressed hydrogen would move over 155 km, from Ludington to Grand Rapids, the nearest industrial hub. The two modes of compressed hydrogen transportation were either a hydrogen pipeline or trucking. Though levelized pipeline transport costs amounted to 0.75 USD/kg, the gaseous pipeline plan was ruled out due to land ownership issues. The costs accounted for a compression facility and 3-day storage capacity. Trucking included the compression facility, 3-day storage capacity, and the cost of diesel-run gaseous tube trailer trucks. Levelized transport costs range from 1.10-1.84 USD/kg[36, 38]. One important thing to note is that these numbers were computed with higher flows of H2 taking place, at 100-200 tons per day (TPD), compared to the scenario at 6.5 TPD produced.

Another consideration was setting up a hydrogen refueling hub in Ludington for hydrogen fuel-cell heavy and medium-duty vehicles, which make up 58% of emissions associated with the transportation energy sector. The Michigan Hydrogen Roadmap emphasized hydrogen fuel-cell heavy and medium-duty vehicles as a major use of green hydrogen for Michigan into the future [39,40]. The levelized cost for the refueling station becomes $2.16-$3.00 [41,42]. This station factors in the compressor, 3-day storage capacity, and the cost of 3 dispensers with a capacity of 1000 kg/day and a lifetime of 10 years. NREL cost calculation of 3 dispensers adds $0.90 to the cost per kg of hydrogen produced.

With the efficiencies in production (~76%), transportation (80-90%), and use in vehicles (40-60%) all relatively low, green hydrogen is not cost-competitive with other production methods of hydrogen [43]. Moreover, with an exponential fall in costs of electric vehicles and a huge drive in technology and demand, hydrogen fuel-cell vehicles are less efficient than electric vehicle direct electrification. Lastly, Ludington has no existing refueling stations, hydrogen demand, or a high volume of industry and population in Ludington [44]. Building a refueling station in those circumstances would lead to an extremely high price of hydrogen borne by the consumer. Therefore, hydrogen fueling stations might be better utilized in other Michigan cities like Flint or Detroit. Furthermore, the DOE's Alternative Fuel Corridor Program and Inflation Reduction Act would provide cost reductions for refueling infrastructure throughout America [45,46].

Green hydrogen will definitely be a key decarbonization fuel in the future, with learning-by-doing projected to drive down costs. As hydrogen projects grow to scale, larger electrolyzers can be adopted; there is a 70% reduction in stack cost by increasing a 10MW per annum scale of electrolyzer by 10 times, to 1 GW per annum [34].

This analysis not only proves that green hydrogen is not yet cost-competitive, but also that ammonia, a product of hydrogen, is not currently competitive with methane and kerosene [47]. Therefore, with the most promising scenarios considered, it would be ideal for the hybrid solution to minimize risk by complementing the existing infrastructure by connecting to the 1,872 MW unit to account for fluctuations in energy supply and demand.

2.9 Port Infrastructure / Vessels

As detailed in section 2.4, the turbines are to be assembled at the port and, subsequently, floated out to the location. The Port of Milwaukee was chosen to complete this assembly process. The second largest port in the state of Wisconsin, Milwaukee also features 6 port-owned crawler cranes with up to 300-ton lifting capacity, allowing for the unloading of heavy turbine components brought in via rail or sea [55]. These cranes will also be used to move the assembled semi-submersible foundations from land into the dock for turbine assembly. Additionally, this port is linked to two Class 1 railroads, infrastructure that will be crucial for the domestic transport of turbine components [55]. In the event transport of turbine components from Europe is needed, the *Rolldock Sky*, a heavy-load carrier compatible with the St. Lawrence Lock network was selected[56]. To perform the turbine assembly, two additional specialized crawler cranes will be assembled on-site. In conjunction, these cranes will be able to hoist the V236's 500+ ton nacelle and 115.5m long blades to heights required for assembly on top of the floating foundation. Additional vessels needed for installation would include SOVs and tugboats to pull the completed turbine assembly out to the site. For operations and maintenance, the chosen vessel is the *Eco Edison*, a Service Operation Vessel (SOV) currently being built and the only SOV compliant with the Jones Act, legislation which requires goods shipped between U.S ports to be transported on U.S-built and operated vessels [57]. With offshore turbines being categorized as U.S ports, foreign ships are effectively barred from domestically loading and unloading turbine components [58]. Additional support vessels such as the *R/V Shackleford*, a hydrographic survey vessel designed to support offshore wind, will be used to survey the proposed location before commissioning [59].

2.10 Risk Assessment

Risk identification and assessment is necessary in informing potential physical failure to the turbine farm, affecting numerous components of the project. Most risk when implementing and operating off-shore turbines derives from weather related events. By assessing the physical risk to the turbine farm, an analysis of which events may trigger physical asset failure was accomplished. This risk assessment focuses on storm-induced gusts, storm-induced waves, and lightning.

Lightning-induced turbine failure is the largest factor in turbine downtime and results in substantial insurance claims; mitigating required lightning-induced damage repairs is essential. Research shows that the risk of lightning strikes increases with the square of height, making the turbines with hub heights of 140 m especially vulnerable [60]. This risk is somewhat mitigated by the naturally moderate flash density over the Great Lakes (Figure 5) [61].To mitigate this risk, the RWE team plans to enlist Det Norske Veritas to ensure international standard Lighting Protection Services according to International Electrotechnical Commission guidelines [62].

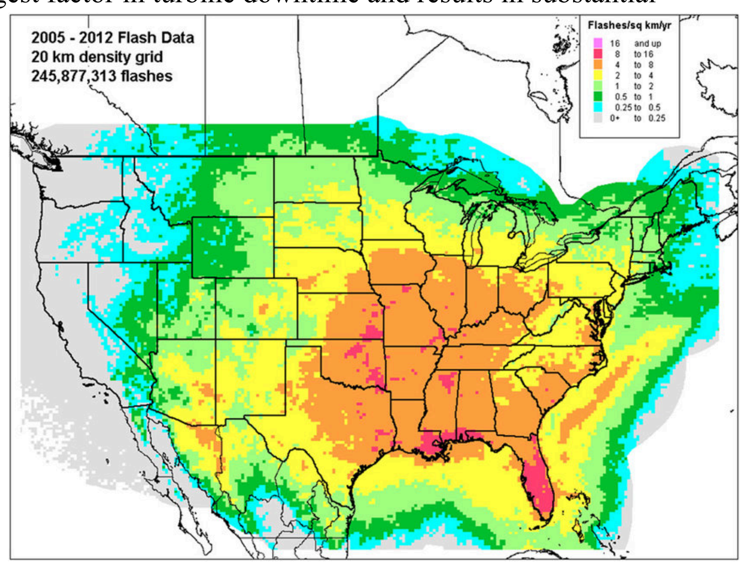

Figure 5: Lighting Flash Density

In-depth research surrounding cyclone/storm related risks was completed by analyzing paths of cyclogenesis through historic climatology. The majority of cyclogenesis that affects the site occurs downwind of the Rocky Mountains and strikes The Great Lakes from the south [63]. The most intense relevant cyclogenesis occurs in the Lower/Mid Mississippi Valley; this is where the project focus will be. As noted before, the site experiences a mean wind speed of 21.4 mph.

Turbine erosion and weathering risks were also assessed and approached with a damage mitigation plan. Fortunately, The Great Lakes' freshwater will not erode the farm's physical assets as quickly as saltwater would [64]. Nonetheless, the team will mitigate this risk by applying a corrosion-resistant coating to the assets most at risk. Marine life such as barnacles may also erode the physical assets, however, this does not need to be considered due to the freshwater characteristic in which barnacles cannot live. In terms of weather-related erosion, the farm will use erosion resistant materials to ensure longevity.

3.0 Financial Analysis

To evaluate the financial viability of the project, RWE identified net present value (NPV), internal rate of return (IRR), and the decision processes associated with them to be the key indicators of commercial success. Under the NPV decision rule, investors and developers alike would only accept positive-NPV projects. This is further corroborated by the IRR decision rule, which states that a project should only be accepted if IRR is greater than the discount rate, which is determined by calculating the weighted average cost of capital (WACC). WACC is defined to be the overall expected return the firm must earn on its existing assets to maintain its value. Through SAM RWE determined project WACC to be 7.18%.

3.1 Initial Capital Cost

The assessment of capital expenditures was divided into two primary components—turbine cost and balance of system costs (BOSC). Given the lack of available financial information surrounding the Vestas V236, NREL's 2023 Annual Technology Baseline (ATB) was used to establish the baseline for turbine cost. Factoring all turbine-related capital expenditures, the ATB establishes a figure of approximately $1,300/kW for offshore wind production in the year 2022 [65]. However, with moderate estimates projecting capital expenditures for offshore wind to fall by over 12% by 2035 [65] as well as continued advancements in offshore wind technology and modularity, a cost of $1,137.50/kW for procuring turbine capital has been applied.

According to documentation for NREL's Offshore Balance-of-System Cost Model, BOS contributes approximately 70% of total installed capital expenditures for offshore wind. This is in stark contrast to land-based wind projects, where BOS only constitutes around 22% of CapEx [66]. This difference can be largely attributed to offshore installations requiring specialized substructures and foundations, as well as increased costs of installation and electrical infrastructure compared to their land-based counterparts. BOSC for the project was determined using the aforementioned NREL Offshore BOSC Model, a sophisticated framework built into SAM with over 100 user-defined parameters designed to quickly and accurately estimate all non-turbine capital expenditures [66]. Soft costs have been accounted for within these parameters. Through the model, BOS and soft cost estimates are divided into seven different categories according to the DOE's system cost breakdown structure (SCBS), totaling $4198/kW [66].

The contribution of each component to capital cost is displayed in the tables below.

Capital Expenditures	Total Installed Cost ($)	Value ($/kW)
Turbine	$ 511,875,000.00	$ 1,137.50
Rotor	$ 155,598,366.46	$ 345.77
Tower	$ 101,793,323.88	$ 226.21
Nacelle	$ 254,483,309.65	$ 565.52
BOS + Soft Costs	$ 1,889,414,590.82	$ 4,198.00
Development	$ 273,435,488.39	$ 607.53
Engineering and Management	$ 95,776,315.02	$ 212.80
Substructure and Foundation	$ 923,768,541.80	$ 2,052.48
Port and Staging	$ 27,097,209.40	$ 60.21
Electrical Infrastructure	$ 330,093,292.30	$ 733.42
Assembly and Installation	$ 214,314,301.63	$ 476.17
Plant Commissioning	$ 24,929,440.58	$ 55.39
Sales Tax	$ 4,802,579.18	$ 11.37
Total CapEx	**$ 2,406,092,170.00**	**$ 5,346.87**

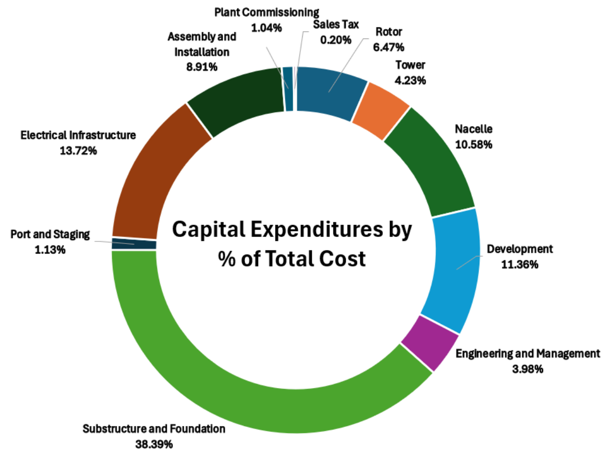

Figure 6/7: Summary of Capital Expenditures and % Allocation of Total Cost

3.2 Annual Operating Expenses

Operations and Maintenance (O&M) costs were projected using NREL's 2023 Annual Technology Baseline (ATB) [65]. NREL estimates fixed O&M costs in 2025 for a Class 11 floating installation as being $80.495/kW. As the need for maintenance increases with the farm's age, an escalation rate of 2.5% is applied to annual O&M costs. However, similar to trends observed in capital expenditures, moderate estimates project O&M costs to have decreased to $73.929/kW by 2030, with a further annual 1-1.5 % reduction through 2050b [65]. To account for this effect, 1.2% was subtracted for a final escalation rate of 1.3%. Placing these inputs into SAM, O&M costs over the project's lifetime were determined to be $970,351,400.00.

3.3 Supply Chain Analysis

RWE analysis of Vestas V236 production and supply chain revealed that Vestas does not currently manufacture the V236 in the U.S. However, the company has announced plans to drastically increase its production footprint on U.S. soil in the near future. To support the production of the V236 for the proposed 810 MW Empire Wind 1 project scheduled to come online in 2026, Vestas has announced plans to construct new production and manufacturing facilities in the state of New York [67,68]. Under the assumption these plans have been executed by RWE estimated construction starting date of 2028, V236 components produced by plants in New York or by other existing Vestas facilities in the U.S. would be shipped by rail to the assembly site at the Port of Milwaukee.

If V236 production is not available domestically, nacelles and blades will be sourced from Vestas factories located in Denmark [69]. Using the heavy load carrier *Rolldock Sky,* components will travel across the Atlantic and be delivered directly to the Port of Milwaukee. This option is far less preferable to the alternative discussed above, as transportation costs will be greatly increased and domestic production incentives will not be met.

3.4 Market Conditions

RWE's wind farm is capable of producing a first-year AC output of 1.711 million MWh, with the ability to maintain an average output of 1.4 million MWh annually over the 20-year life-span of the project. The average retail price of electricity in Michigan is $181 per MWh, while the national average is $161 per MWh [70]. RWE is extremely competitive at both levels in part due to the new and extremely efficient Vestas V236 turbine in a large 30-turbine group, which allows the project to take advantage of the economical scaling effect of this type of project.

As Michigan currently has some of the highest electricity prices in the U.S. the project's entry into the market would help reduce those costs. Given that there already exist onshore wind farms in the region, RWE expects the community near the project to view wind energy positively, which makes the construction of such a facility easier when it comes to policy issues. Furthermore, the project will bring employment opportunities, contribute greatly to boosting the local economy with renewable energy jobs, and provide affordable clean energy to Ludington and surrounding Michigan towns. These factors, combined with the prospective reduction in energy cost, make RWE's proposed wind farm an extremely compelling case for the locals of Ludington Michigan to support. And, although Michigan has a relatively high level of renewable energy usage, natural gas still makes up 45.8% of the state's energy profile [71]. This dependency has shown its vulnerability during the Russian invasion of Ukraine, which significantly increased the retail price of natural gas. Shifting Michigan's energy consumption towards wind energy would make strides toward stabilizing the cost of energy in the state since natural gas is a commodity that is heavily affected by geopolitical conflict. The project use of a Power Purchase Agreement (PPA) adds to this pricing stability by allowing the utilization of a locked-in price with the energy company and the consumer. The PPA will be contracted with Michigan energy giant Consumers Energy as a project partner. This company also owns Ludington Pumped Storage Plant, one of the largest hydroelectric energy storage facilities in existence, meaning the farm will be able to interconnect through the local substation [72]. This PPA aligns with Consumers Energy 2021 Clean Energy plan to increase their energy generation to 90% renewables in the next 20 years [73]. Through this pricing structure, competitive pricing for the state of Michigan can be guaranteed. Up North Utilities is planning to construct a high-voltage power transmission line from Ludington to Milwaukee, which would open up another market in Wisconsin for RWE to provide energy. Wisconsin's electricity retail price is currently $170/MWh, meaning the PPA price would continue to be competitive across state lines [74]. These conditions make RWE's project highly economical in the current Midwest energy market.

3.5 Taxes and Incentives

A major stimulus towards the realization of this project is the Inflation Reduction Act (IRA) of 2022. The largest U.S federal renewable energy investment in history, the IRA extended offshore wind's eligibility for two major tax credit incentives: the Production Tax Credit (PTC), a production-based incentive which can a corporate tax credit of up to 2.75 ¢/kW of energy generated for 10 years, and the Investment Tax Credit (ITC), an equity-based incentive that can provide one-time a base credit up to 30% of capital costs if certain apprenticeship and wage requirements are satisfied [75]. As the PTC and ITC are mutually exclusive and deliver their benefits in very different ways, it was necessary to determine which credit would be more beneficial to our project. Research indicates the PTC is superior for projects with lower equity costs and higher capacity for production, whereas the ITC is better suited for projects with high upfront capital costs [76]. Accordingly, given the high upfront capital costs associated with offshore wind, it was decided that the ITC would offer far greater value than that of the PTC. This hypothesis was subsequently verified using SAM, where simulations performed under a 30% ITC provided over $200 million more in investor value than a 2.75 ¢/kWh PTC. The gap between the ITC and PTC only grew further after factoring in available 10% bonus credits. The application of these credits exhibits a much greater effect on the ITC compared to the PTC, as they are applied additively rather than multiplicatively [76]. For example, a recipient of the 10% Energy Community Bonus would now receive a flat 40% ITC, a 33% increase in value, whereas the PTC would escalate to 3.05 ¢/kW, a mere 11% increase in value.

In addition to the full 30% ITC rate, the apprenticeship and wage requirements that RWE will fulfill, our research and projections indicate two additional bonus incentives available to our project. The first of these bonuses is the aforementioned Energy Community Bonus, a 10% incentive granted to qualified projects under one of three stipulations based on project location and economic conditions in the region [77]. Qualified projects are either (1) constructed on a brownfield site, (2) are located in an area meeting Fossil Fuel Employment (FEE) thresholds with the unemployment rate at or below the national average, or (3) are located in a region in which a coal mine closed after 1999 or had a coal-fire eclectic generating unit retired after 2009 [77]. According to U.S. DOE mapping of eligible areas, the proposed location at Ludington, MI satisfies all stipulation (2) requirements, granting RWE eligibility for the full Energy Community Bonus [78]. RWE is also seeking an additional 10% Domestic Content Bonus to the ITC, applied to projects consisting of at least 55% domestically manufactured parts [77]. As discussed in the supply chain analysis found in section 3.4 above, under the assumption domestic production of the V236 has begun by 2028, RWE's total incentive total under the ITC would be brought to a cumulative total of 50% of all capital expenditures. If domestic production is unable to be procured, RWE's ITC qualification would fall to 40%. The impact of this change on investor value can be seen in section 3.10 below.

Furthermore, although not currently accessible to industrial-scale renewable energy projects, RWE hopes to claim benefits from the Michigan Business Tax program, which advances renewable energy development in the state. Given Michigan's intention to grow its renewable energy industry over the next decades, it is anticipated that the program will grow to include larger projects in the future. RWE also plans to obtain a significant property tax exemption from the state of Michigan. As a renewable energy development, RWE's project is eligible for the establishment of a Michigan State Renewable Energy Renaissance Zone (RERZ). Upon the establishment of the zone, RWE will be exempt from Michigan property taxes [79].

Altogether, these tax incentives play a major role in reducing financial responsibilities on the investor, reducing risk and greatly increasing project profitability and viability.

3.6 Financial Assumptions

As per NREL projections from the 2021 Cost of Wind Energy Review, RWE assumes a federal income tax rate of 21%, an annual insurance rate of 0.349% of installed costs, and a nominal debt interest rate of 4.0%. Although RWE is exempt from state property taxes under the RERZ, a Michigan corporate income tax rate of 6% and a state sales tax rate of 6% still must be applied. Annual insurance rates for wind turbines were found to range from $8,000-$15,000. Given the size of Vestas V236 turbines and the immaturity of the floating offshore wind industry, a conservative estimation of $14,000 is applied. This correlates to an annual insurance rate of 0.349% of installed costs. RWE further assumes a nominal capital recovery factor of 7.3% of installed cost. The nominal discount rate was set to be equal to RWE's simulated WACC of 7.18%. Finally, the inflation rate is assumed to be 2.5% a year.

3.7 Depreciation of Assets

In addition to tax incentives, accelerating the depreciation of assets can play a major role in increasing project value. The sooner capital is fully depreciated, the sooner full tax deductions can be claimed. Accordingly, RWE plans to make full use of the 5-year Modified Accelerated Cost Recovery System (MACRS) available to U.S. wind projects [80,81]. Under a moderate assumption that 98% of RWE assets will be depreciable and eligible for the 5-year allocation, the application of MACRS in SAM reveals a tax saving of $182,210,456.00 over 20-year straight-line depreciation. The remaining 2% of assets is assumed to be non-depreciable.

3.8 Financing plan

The typical financing configuration of a wind farm project is roughly 40% through borrowed loans and 60% from investors. Bank of America is committing $1.5 trillion towards investing in renewable energy to accelerate environmental transition, while JP Morgan has pledged over 2.5 trillion for the same purpose. The project will feature a partnership with both of these banks as equity providers [82]. RWE plans on partnering with these banks to finance a PPA with debt, which has several advantages. First, it is appealing to consumers because there is no upfront cost until the farm begins generating energy. Secondly, a PPA locks in pricing for a period of twenty years, meaning that the pricing is stable and often cheaper than competing options. It splits the risk between the consumer and the producer. A PPA will produce a stable revenue stream for the life of the project, meaning that unless a rare problem occurs that severely impacts production, the contract will protect buyers, sellers, and investors from price fluctuations. Finally, PPAs are considered secure investments for banks, which means that partners such as BofA are more willing to partner with the project.

The banks will form a 95/5 tax flip and 95/5 cash flip structure, which is the industry standard for renewable energy projects. Essentially, equity partner banks will agree to 95% of the project's equity until the sixth year. Following the flip year, the investors will assume 5% of tax and cash benefits while the remaining 95% will go to RWE. According to NREL's 2023 Offshore Wind Market Report, LCOE will range from $66-$128/MWh by the year 2030. In order to avoid severely undercutting Michigan power prices, we seek a PPA price of $0.0947/kWh, or $94.7/MWh escalating at an annual rate of 2%.

3.9 Optimization Process

In order to increase investor value, RWE focused optimization efforts on three primary areas: optimization of wind resources, optimization of farm layout, and optimization of capital costs.

Under an initial understanding that wind resources increase further offshore, the goal of this optimization process was to determine the longitude at which negative NPV from increases in cabling costs would begin to outweigh the positive NPV derived from greater outputs due to higher wind speeds. Based on Michigan–Wisconsin state lines, RWE first established an initial 40x40 km boundary off the coast of Ludington. Within this perimeter, extensive simulations were performed using SAM to pinpoint an ideal location for the project. By continuously varying the location of the farm and recording investor IRR, a logarithmic relationship between NPV and distance from shore was observed, results which revealed the -86.5714 longitude line approximately 10-15 km offshore to be the value trade-off region between increased wind speeds and increased cabling costs. Additional latitude-wise testing revealed little variance in available wind resources on a north-south axis. Based on this analysis, the final location was set to be 12.8 km offshore at (43.8895, -86.6020), a 15,914-acre plot that avoids major shipping lanes in the region.

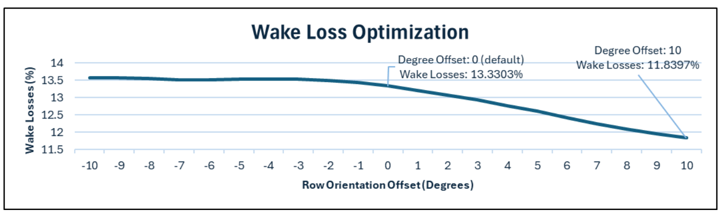

Figure 8: Wake loss % vs Row orientation offset (degrees)

Optimization of farm layout was defined to be in terms of minimizing wake losses between the 30 turbines. An initial minor optimization was made by offsetting the middle row of turbines by 2.5 rotor diameters, reducing total wake losses by 0.1%. Further wake loss optimization was conducted in SAM by varying the row orientation of the turbines by 10 degrees in each direction, a rotational bound determined in Furrow beyond which shipping lanes would be affected.

As seen in the graph on the left, SAM simulations revealed that offsetting row orientation by 10 degrees reduces wake effect losses by approximately 1.5%. A corresponding positive effect can be seen in the capacity factor, which jumped from 42.69% to 43.42%, a significant increase of over 0.7%. Through these two option processes, RWE successfully reduced wake losses by 1.6%, leading to a jump in investor IRR from 20.84% to the final simulated value of 21.10%.

Finally, capital costs were reduced by researching, adjusting, and simulating inputs to SAM's Offshore Balance of System Cost Model. For example, inputs concerning installation vessel strategy and turbine install weather contingency were determined to be somewhat redundant by the in-port installation strategy, so their cost factors were reduced accordingly. Furthermore, we used SAM's built-in electrical cable cost optimizer to automatically select the most appropriate and cost-effective cable sizes for the turbine layout, with cable voltages being adjusted manually to correspond to the project's transmission npv design. These factors combined to reduce the simulated BOSC from $4,634.94/kW to $4198.00/kW, a capital expenditure savings of 9.6%.

3.10 Cash Flows and Investor Value

The following graphs provide a full financial summary of cash flows over the project's lifetime.

Incentive	Internal Investor IRR (%)	Project End Investor IRR (%)	Project Life Investor NPV ($)	Project End Developer IRR (%)	Project Life Developer NPV ($)	Nominal LCOE ($/kWh)	Real LCOE ($/kWh)
40% ITC	12.29%	13.07%	$96,796,680	14.59%	$148,205,728	0.0979	0.0797
50% ITC	21.10%	22.04%	$209,584,544	23.54%	$269,851,168	0.0838	0.0682

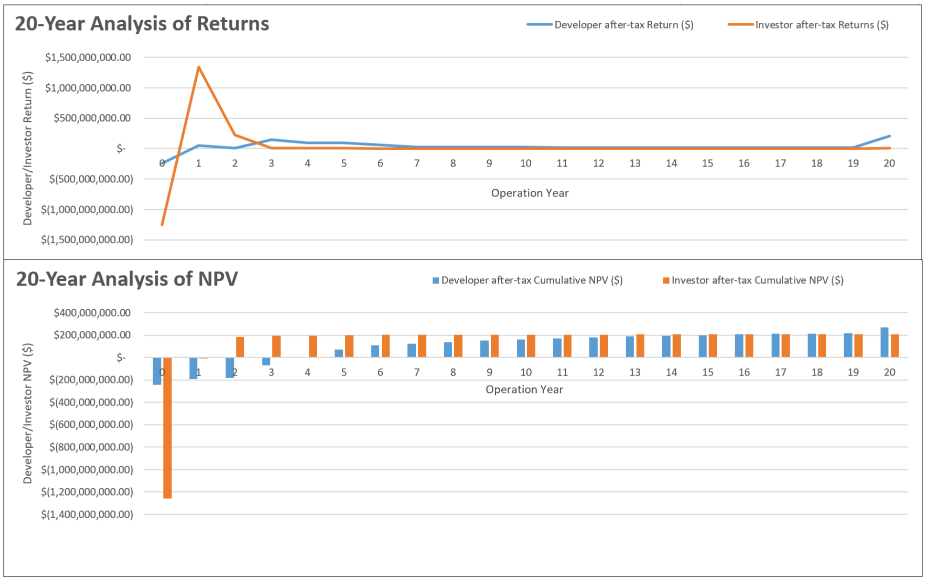

Figure 9/10/11: Summary of lifetime project cash flows

4.0 Lease Bid

The lease for RWE's project will be under the jurisdiction of the state of Michigan, specifically the Department of Environment, Great Lakes and Energy. One of this department's many jobs is overseeing Great Lakes Bottomland Conveyances or the leasing of portions of the Great Lakes on its borders. The only leases for bottomlands currently available are for lakefront property owners and marinas [83]. The pricing of these leases is based on a percentage of the price of the surface-level property [84]. Therefore there is no precedent for the sale of bottomlands not connected to a shore property. However, under Michigan's Department of Natural Resources, there is a precedent for the leasing of state-owned land. Currently, 1 acre of land for the use of oil or mineral extraction is 10 dollars a year [85]. When comparing this value to recent sales of leases for offshore wind farms in the Atlantic, the value is very small. In the state of New York, based on sales that occurred in February 2022, 1 acre costs range from 200 to 324 dollars per year. That being said, in the state of Louisiana, based on a sale that occurred in August 2023, 1 acre costs 1.41 dollars per year [86]. This sale is more similar to RWE's project area in that the lease area for the Louisiana sale was in an undeveloped area and was the first lease to be sold in the Gulf of Mexico for offshore wind. Based on these pieces of information RWE is willing to bid $37.16 million. This bid is equivalent to 1 acre costing $100 per year, given the size of the project is 14,864 acres and will need a lease for 25 years. This price is 10x the precedent for land leased out by the State of Michigan, the increase ensures that the bid is competitive.

Resources

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