Horizon Offshore Wind Farm

2024 Collegiate Wind Competition
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1.0 Executive Summary

The developers at WiscWind LLC present Horizon Offshore Wind Farm: a 525 MW floating offshore wind farm located in Lake Michigan with an average wind speed of 9.17 m/s. The project consists of 35 Vestas V236 15 MW turbines with a net annual energy production (AEP) of 2,204,793 MWh/year and a capacity factor of 48%. The commercial operation date (COD) is anticipated to be 2033, with construction beginning in 2029. WiscWind LLC will sell the energy generated through a Power Purchase Agreement (PPA) with Consumers Energy at a rate of $123/MWh. Capital and operational expenditures were calculated along with a financing plan for the project that generates a Levelized Cost of Energy (LCOE) of $119/MWh. The wind farm will be coupled with a lithium-ion Battery Energy Storage System (BESS) built by Consumers Energy at the repurposed JH Campbell Generating Complex in Port Sheldon, Michigan.

2.0 Site Selection and Description

2.1 Site Selection Process

The developers at WiscWind LLC have conducted extensive research and analysis to identify a suitable site for the Horizon Offshore Wind Farm. To assess the wind energy development potential of Lake Michigan and Lake Superior, factors including wind resource, bathymetry, conflicting use, port proximity, and environmental considerations were assessed. Raster layers were created in ArcGIS Pro[1] for all factors, based on relevant data. The data from the raster layers were scored on a scale of 0-10, with 10 being the most favorable to wind energy development. The factors were then weighted based on their importance to developmental success of the project. Each layer was then multiplied by the factor weighting and combined into a raster overlay displaying overall score. Details about each factor are as follows:

Wind Resource Assessment: Wind resource data was obtained from the Global Wind Atlas[2]. Wind speed was given a weight of 30% in the raster overlay, the highest of all the factors. This is because wind resource is the most important aspect of power generation and therefore the main source of revenue for the project. Furthermore, wind speeds vary from 6.17 m/s to 10.42 m/s across the Great Lakes at 150 meters, so power generation will vary greatly.

Bathymetry: Bathymetry data was obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information Program[3]. Based on this data, floating foundations were determined to be a necessary solution in most areas, as high-water depths are common in the Great Lakes. Bathymetry was assigned a weighting of 20%, which was the lowest since differences in depth are not as significant for floating versus fixed-bottom turbines.

Conflicting Use and Environmental: Within conflicting use, four subcategories were examined and weighted: vessel traffic, recreational activities, protected areas, and viewsheds. Marine protected areas were considered unusable and identified using the NOAA's Marine Protected Area Viewer[4]. Vessel traffic was identified with the AccessAIS[5] tool from Marine Cadastre and given a subcategory weight of 30%. Any major shipping and ferry lanes were also avoided in final site selection. Distance from shore was evaluated using a raster layer created in ArcGIS Pro[1] and given a subcategory weight of 70%. It is the highest weighted subcategory as most recreational activities, vessel traffic, and important wildlife areas are near the coast[6]. The overall conflicting use category got a weight of 25% as it had substantial variance across the lease area and could provide significant project development constraints.

Port Proximity: At first, previously identified ports feasible for offshore wind energy development were considered.[7] A raster layer for each port was then created in ArcGIS Pro[1] that measured the distance from that port to all locations in their respective lakes. Additionally, a score out of 10 was given to each port that represented the extent to which its current infrastructure would need upgrading, which was applied to the overall heat map. This factor was given a weight of 25% because available port infrastructure plays a larger role in Great Lakes offshore wind energy development[7]. These initial "port proximity" layers for each port were eventually replaced with a single "distance to interconnection" layer to the chosen point of interconnection: the JH Campbell Complex.

The overall site selection heat map was updated through the optimization process and is shown in **Figure 1** along with the initial site selection heat map. The optimized site specifics are in the optimization process section.

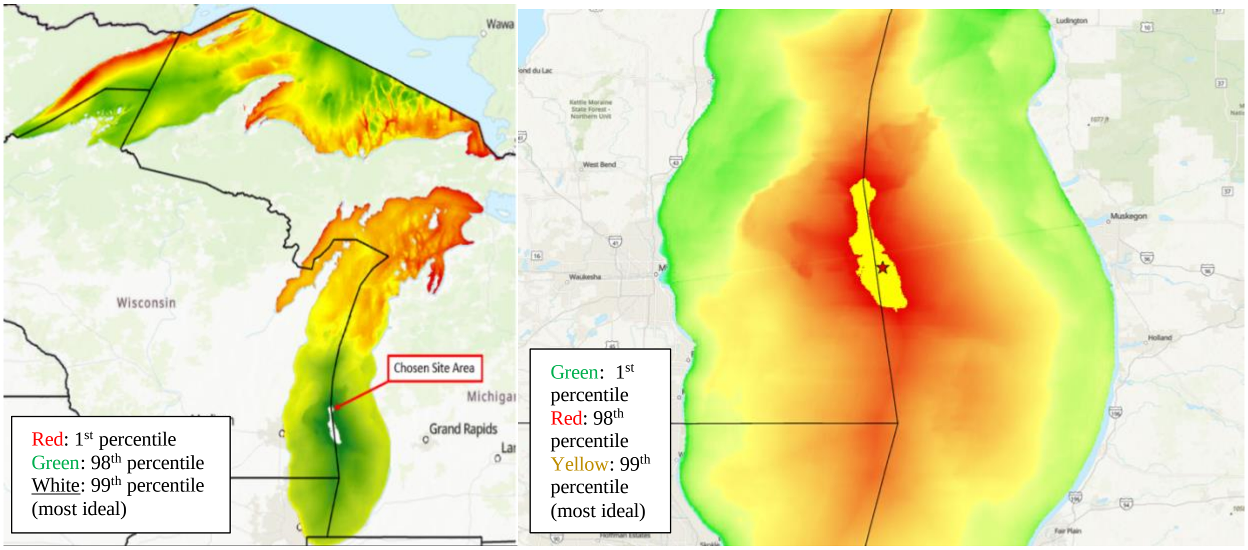

Figure 1. Total scores with original site location (left) and optimized scores with new location (right).

2.2 Wind Resource Assessment

To assess the wind resource at the Horizon Offshore Wind Farm, data was purchased from Vortex FDC[8] for a central location relative to the chosen site area. This data was modeled by the ERA5 atmospheric reanalysis method at one-hour intervals over the course of 12 years, starting in December 2012 and ending in November 2023. To analyze the data, provided at a height of 150 meters, Microsoft Excel[9] was employed. **Table 1** breaks down the percent time that wind blows from each direction and is accompanied by **Figure 2,** which is a wind rose created in MATLAB[10]. As the wind rose shows, the prevailing wind direction was from the SSW and wind blew the least frequently from the ENE direction. However, the wind direction is variable as the wind consistently blows from the WNW and NNE directions. The average annual wind speed at the site is 9.17 m/s. Wind speed values were binned by their frequencies into 1 m/s intervals and fitted with a Weibull curve as seen on the right in **Figure 2**.

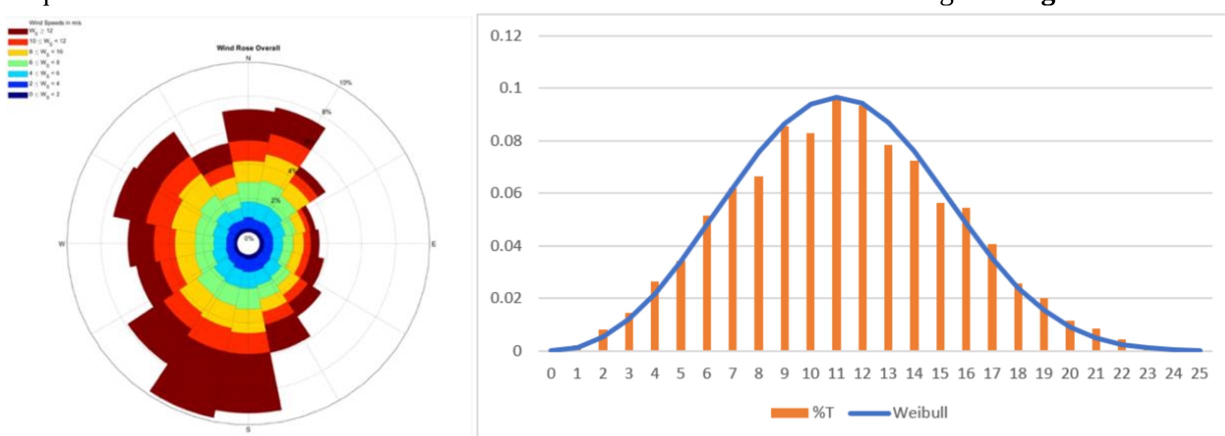

Figure 2. Wind rose (left) and wind speed distribution (right).

Table 1. Average wind direction at the Horizon Offshore Wind Farm as a percent time.

Direction	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
%T	7.22%	7.48%	4.79%	3.36%	3.51%	3.86%	4.49%	5.88%	9.31%	9.77%	7.86%	6.05%	6.42%	7.43%	7.23%	5.35%

The data was also analyzed for diurnal and seasonal patterns. The average wind speed for each hour of the day and all months of the year was calculated. The diurnal and yearly variation are shown in **Figure 3**. From this analysis, wind speeds varied from 8.10 m/s around 11:00 am to 10.05 m/s around 11:00 pm. Over the course of a year wind speed varied from 11.80 m/s in November to 6.00 m/s in August.

		Hour of the Day																							
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Month of the year	1	10.66	10.61	10.51	10.38	10.17	9.87	9.76	9.79	9.84	9.89	9.88	9.81	9.74	9.68	9.65	9.66	9.73	9.81	10.08	10.31	10.51	10.66	10.70	10.70
	2	10.77	10.74	10.71	10.67	10.52	10.24	10.15	10.23	10.27	10.25	10.19	10.09	10.01	9.99	10.06	10.04	9.99	9.94	10.09	10.29	10.45	10.58	10.72	10.78
	3	10.09	10.11	10.08	10.03	9.91	9.62	9.52	9.57	9.55	9.48	9.36	9.24	9.21	9.23	9.29	9.24	9.18	9.19	9.52	9.85	10.02	10.08	10.10	10.12
	4	10.57	10.54	10.49	10.35	10.15	9.84	9.75	9.72	9.66	9.56	9.44	9.28	9.14	9.22	9.41	9.47	9.47	9.49	9.66	9.93	10.27	10.54	10.62	10.60
	5	9.69	9.60	9.47	9.33	9.21	9.06	8.99	9.00	8.93	8.72	8.49	8.40	8.49	8.58	8.76	8.90	8.92	8.79	8.80	8.97	9.27	9.43	9.52	9.59
	6	8.85	8.83	8.72	8.60	8.45	8.23	8.01	7.98	7.87	7.62	7.49	7.52	7.63	7.83	8.09	8.28	8.29	8.13	8.12	8.21	8.34	8.49	8.61	8.77
	7	7.99	7.94	7.90	7.78	7.60	7.21	6.99	7.00	6.94	6.76	6.62	6.57	6.66	6.85	7.12	7.22	7.20	7.13	7.15	7.20	7.29	7.49	7.76	7.91
	8	7.57	7.54	7.49	7.38	7.24	6.97	6.74	6.67	6.62	6.48	6.33	6.28	6.32	6.49	6.72	6.85	6.89	6.82	6.84	7.00	7.19	7.39	7.46	7.56
	9	9.14	9.14	9.09	8.93	8.71	8.40	8.15	8.12	8.10	8.04	7.99	7.95	7.94	7.94	7.97	7.96	7.94	7.92	8.05	8.29	8.52	8.75	8.93	9.07
	10	10.11	10.12	10.14	10.07	9.96	9.77	9.73	9.76	9.78	9.75	9.61	9.44	9.34	9.33	9.39	9.44	9.43	9.42	9.59	9.83	9.98	10.09	10.17	10.22
	11	11.14	11.05	10.96	10.80	10.62	10.36	10.26	10.32	10.41	10.45	10.45	10.42	10.39	10.41	10.51	10.62	10.69	10.77	11.00	11.19	11.24	11.19	11.16	11.14
	12	10.50	10.48	10.42	10.32	10.19	9.98	9.96	10.08	10.15	10.11	10.04	9.95	9.85	9.78	9.80	9.80	9.83	9.91	10.19	10.34	10.40	10.43	10.44	10.47

Figure 3. Typical year wind speeds at the Horizon Offshore Wind Farm.

2.3 Detailed Site Layout

The layout of Horizon Wind Farm consists of 35 x 15 MW Vestas V236 wind turbines with five rows of seven turbines each. There is a 6 rotor-diameter (RD) spacing between each turbine and each row, and every other row is offset by 3 RD. Since the V236 specifications are not publicly available, the IEA 15 MW[11] turbine was used to estimate its capabilities and characteristics for designing the wind farm. Turbines were oriented to the southwest at a heading of 200°, which optimizes energy production.[12] The total area of the site was calculated in Google Earth[13] to be 44.7 km^2 and its roughness coefficient was estimated to be 0.1, since the site is open water[14].

Figure 4. Turbine layout, electrical infrastructure, and export cable to JH Campbell substation.

The inter-array electrical infrastructure consists of 50.7 km of 66 kV-rated cabling. Five individual cable lines will run parallel to each other from the west of the site to the offshore substation at the eastern end shown in **Figure 4**. On each line, seven turbines will be connected in series suspended in midwater column. and then connected to the substation located 6 RD away from turbine 15. At the offshore substation, the voltage will be stepped up by transformers to 238 kV and transported 62.9 km via an export cable buried 2 m deep to an onshore substation. The JH Campbell Generating Plant in Port Sheldon, Michigan was chosen as the interconnection facility to utilize existing electrical infrastructure; this site will also host the battery storage system. This also avoids laying transmission lines through the Wisconsin Shipwreck Coast National Marine Sanctuary and the Southwest Michigan Great Lakes State Bottomland Preserve[4]. The current substation at JH Campbell was examined with the U.S. Energy Atlas and was found to have a voltage of 128kV[15]. The substation was also determined to have the necessary room for physical expansion and will be improved to handle a voltage of 238kV.

2.4 Turbine Technology

Turbine technology considerations in the Great Lakes region are different than for ocean-based offshore wind projects primarily due to the increase in access constraints for both supply chain and supporting construction vessels because of the St. Lawrence seaway. These constraints primarily apply to projects using fixed-bottom turbines, as floating projects do not require the large wind turbine installation vessels (WTIVs) needed to construct the bigger turbines, which are typically limited to 6 MW.[7] To select a turbine type, a parametric analysis of the effect of turbine capacity on the levelized cost of electricity (LCOE) was conducted. NREL's System Advisory Model (SAM)[16] was employed to compare three models: the Vestas 164 8 Megawatt (MW), the 2020 ATB NREL Reference 12 MW, and the IEA 15 MW RWT. For each scenario, the total capacity of the wind farm was set to 240 MW, with 8 x 8 rotor diameter (RD) spacing, and a hub height of 150 meters. The same wind data acquired from Vortex[8] above was used. For the 8 MW, 12 MW, and 15 MW units, the expected LCOEs were $0.072, $0.068, and $0.063 respectively. The analysis revealed that the larger turbines are more cost-effective, as they allow the project to take advantage of the economies of scale and increase wind farm efficiency.

After analyzing different sizes of turbines, two 15 MW models were compared: the Vestas V236 turbine and the Siemens Gamesa 14-236 DD turbine. The turbine models are very similar, and both have serial production scheduled for 2024. The Vestas V236 turbine has a rated power of 15 MW[17], while the Siemens Gamesa 14-236 DD turbine has a nominal power of 14 MW[18]. Additionally, both models use a permanent magnet generator and have currently installed prototypes. Ultimately, the Vestas V236 turbine was selected because it is further along in the design process and is more likely to be available when construction starts, and its prototype successfully began producing power in December 2022[19].

2.5 Foundation Technology

Floating foundations will be utilized for the Horizon Offshore Wind Farm due to specific challenges posed by the vessels required for fixed-bottom foundation installation and construction. These vessels exceed the size limits for locks connecting the Great Lakes, and at an average depth of 85 meters, the chosen site is too deep for traditional foundations.[7] Use of floating foundations circumvents the need to employ such vessels. Horizon Offshore Wind Farm will use floating semisubmersible concrete hull technology, which has shown potential to reduce foundation costs of floating offshore wind farms and is being tested in the New England Aqua Ventus pilot project[20]. The anchor type selected was suction pile for various technological reasons. For example, the holding power of suction pile anchors is preserved when the anchor rotates, whereas plate-type anchors like drag embedment can lose resistance, resulting in the mooring lines losing holding power[21].

2.6 Port Infrastructure

The chosen wind farm site is within Michigan state boundaries, so keeping most project operations and economic benefit in Michigan is a priority. After analyzing the current infrastructure of the most feasible ports in Michigan for offshore wind[7], it was determined that the Port of Muskegon would be used for Horizon Offshore Wind Farm. For floating offshore wind turbines, the estimated area required for staging and installation is 30 – 100 acres, which the Port of Muskegon does not currently have.[22] Significant upgrades will be needed to support assembly and installation for floating offshore wind technologies. However, the project may be able to obtain a Department of Transportation RAISE grant to aid with the capital costs associated with upgrading the Port of Muskegon.[23] The project meets applicant requirements on the basis that Muskegon port area is a characterized coal closure energy community and the usage of the upgraded port would bring jobs and clean energy.[24] WiscWind LLC will employ two barges with land-based cranes at the Port of Muskegon to aid with space constraints at the port[7]. According to an industry professional interview[25], the delivery of components is restricted to around three turbines at a time due to vessel constraints, so the floating turbines will be assembled at the Port of Muskegon and then towed out to the site[7]. The barges will be used as temporary workspace for assembly on the quayside of the port, which has been done various times before in the industry.[25]

While the initial design used the JH Campbell Complex as a location for a custom offshore wind port, after further analysis was conducted, it was determined that the long-term potential gain of a custom port would not outweigh the higher capital costs that would make it unattractive to investors. The port leasing option reduces capital costs and makes the project more feasible. Therefore, after careful analysis of multiple factors, the Port of Muskegon will instead be utilized during construction and maintenance of Horizon Wind Farm.

2.7 Vessels

Throughout the lifecycle of an offshore wind farm, specialized vessels are crucial for tasks ranging from development and construction to maintenance and decommissioning. These vessels are bound by the Jones Act of 1920, which restricts access to U.S. ports to vessels built, owned, and operated by U.S. citizens or permanent residents.[26] Fincantieri Marine Group, with three locations on Lake Michigan, specializes in constructing Service Operation Vessels (SOVs) for wind farms.[27] Their VARD 4 19 US Windfarm SOV is tailored for transporting personnel and equipment to and from offshore wind farm locations and serves a role in maintenance and support, with heavy-duty cranes and dynamic positioning systems engineered to install and maintain wind turbines.[28] For towing floating foundations to installation sites, the Hull 749 Fincantieri tugboat will be deployed.[29] The Fincantieri seismographic research vessel will be employed to collect environmental, geophysical, and hydrologic data prior to installation. Additionally, Kokosing's Dynamic Positioned Barge (DP-2) is designated for laying the underwater cables, ensuring the efficient and precise installation of essential infrastructure.[30] In the event of icing interfering with maintenance and other necessary support, a request for aid from ice-breaking boats employed by the United State Coast Guard (USCG) may be necessary.

2.8 Hybrid Power Plant Design

Battery Energy Storage Systems (BESS) are a suitable technology to integrate with offshore wind farms, offering a practical solution to wind curtailment challenges. They help ease grid pressure and maintain a steady electricity supply despite fluctuating wind conditions[31]. Replacing fossil fuel plants with new forms of power generation is essential to keeping electrical grids reliable, especially in the Midwest. In 2023, the North American Electric Reliability Corporation (NERC) designated the MISO grid as high risk. Beginning in 2028, MISO expects a 4,700-MW power shortage in the Midwest region if expected fossil fuel power plant retirements occur[32]. The generation from Horizon Offshore Wind Farm will help alleviate the stress on the MISO grid. However, there are limitations with this technology, such as the need to place storage close to the wind farm or upstream of transmission constraints for optimal effectiveness[33]. Additionally, the variable temperature ranges near the Great Lakes can pose material constraints. While careful consideration of these challenges is crucial for successful integration in the Great Lakes, BESS emerges as a valuable and promising technology.

BESS was chosen over other generation and storage technologies such as floating solar photovoltaic farms (FPVs), pumped hydro energy storage, and gravity-based storage[34]. FPVs are a growing technology similar to offshore wind farms[35]. New projects utilizing this technology include projects off the Dutch coast and a hybrid project utilizing both offshore solar and wind technologies off the southern Italian coast.[36,37] While FPVs could be implemented in Horizon Offshore Wind Farm in a similar fashion to developer Solar Duck's installation off the Italian shore, potential environmental challenges, lack of research, and subsequent financial concerns for long-term performance and reliability of FPVs resulted in the decision to utilize BESS as a hybrid method instead. Other storage technologies were also considered, such as pumped hydro energy storage and gravity-based energy storage. However, hydro energy storage requires a significant level of elevation that the nearby geographical features do not support. BESS is also a more proven and cost-efficient technology than gravity-based storage, a more nascent technology developed by Energy Vault[38].

Repurposing the JH Campbell Generating Plant

Horizon Offshore Wind Farm will combine the power generation of offshore wind technology with the storage capacity of a Battery Energy Storage System (BESS) at the retiring JH Campbell Generating Complex site in Port Sheldon, Michigan to service the Midcontinent Independent System Operator (MISO) grid. The JH Campbell Generating Plant is owned by Consumers Energy, and both battery storage and wind power fit within Consumers Energy's Clean Energy Transformation plan[39]. The JH Campbell site is approximately 2,000 acres and includes both Lake Michigan and Pigeon Lake frontage as well as railway access[40]. The redevelopment areas outlined in the JH Campbell Stakeholder Update from Consumers Energy provide ample space for the development of battery storage, as well as existing electrical structure that can be implemented into the BESS design[40]. Furthermore, the power produced by Horizon Offshore Wind Farm will go directly towards replacing JH Campbell's 1420 MW capacity and will allow the hybrid plant to act as a baseload power source[41].

2.9 Annual Energy Production

Several factors went into calculating the net annual energy production (AEP) for Horizon Offshore Wind Farm, which is estimated to be 2,204,793 MWh/year. This AEP was calculated by estimating the gross annual energy production and subtracting losses due to wake effects, electrical losses, unavailability losses, and other losses such as curtailment, underperformance, and environmental factors.[42] First, the gross annual energy production (AEP) of Horizon Offshore Wind Farm was calculated in Excel, using wind data previously acquired from Vortex.[8] The IEA 15 MW reference wind turbine power curve[43] was multiplied by the average annual Weibull distribution to yield a value of 2,718,946 MWh/year. Electrical losses were estimated to be 3%, availability losses were estimated to be 4%, and other losses were estimated to be only 1% since battery storage decreases grid curtailments.[42,31] An additional 0.2% loss from icing was applied as recommended by SAM.[16] Wake losses from the established layout were calculated to be 10.7% using Furow.[8] Finally, the total losses of 18.9% were subtracted from the calculated gross AEP to yield a net AEP of 2,204,793 MWh/year and a capacity factor of 48%.

3.0 Environmental Considerations

Species of Concern

WiscWind LLC reviewed potential harmful impacts to local wildlife. Zooplankton are a vital component of Lake Michigan's food web as they are a prime food source for most of the lake's fish species.[44] Disturbance to upwellings where zooplankton thrive can disturb the lake's ecosystem; however, this issue is minimal as upwellings are primarily along the lake's shoreline, far from the project site.[45]

Benthic amphipods, such as worms and mollusks, provide food for native fish species such as yellow perch and burbot.[46] The foundation, anchor and cables that will be utilized, as well as their installation process, may alter the benthic environment during and after construction. However, the specific issue of sediment displacement tends to be temporary, and recovery usually occurs within a few years.[47] In addition, the anchor foundations rest in a small area of the lake bottom. While anchors that are left in place cause permanent changes to the benthic habitat, the minimal surface area of the anchors results in habitat loss of less than 1% of the windfarm area.[47] Mooring lines may also pose a concern of entanglement for large pelagic species. However, these lines are made of thick chains or cables, unlike common entanglement threats such as fishing netting. Therefore, this risk is minimal.

Migratory bird patterns are also considered, as the windfarm is in the Mississippi and Atlantic flyways,[48] making it a hazard for local and migratory species, some categorized as endangered. Common migratory birds include Canada geese, Sandhill Cranes and Sandpipers.[49] Whooping Cranes are also a common migratory bird utilizing the Atlantic and Mississippi flyways that is listed under the Endangered Species Act (ESA) as endangered.[50]

Mitigation Measures

Noise pollution is a significant environmental concern that will be met with direct mitigation measures. During installation, there will be continuous monitoring such as noise impact assessments to limit harmful effects to the surrounding ecosystem. The general construction process and structure of a floating wind farm design is significantly less disruptive to benthic and pelagic ecosystems in comparison to non-floating wind farm structures due to the lack of pile driving. Additionally, the number of species impacted by noise pollution in Lake Michigan is significantly less than oceanic habitats. Marine mammals such as whale and dolphin species are not a concern for a Lake Michigan site location.

In terms of mitigation to prevent harm to migratory birds, there are various solutions to prevent collisions with turbines. Solutions include painting the rotor blades black to reduce their motion smear and utilizing bird detection technology such as IdentiFlight to curtail individual turbines when birds are detected nearby.[51,52] IdentiFlight technology utilizes machine vision in addition to artificial intelligence. Automatic detection and species identification occur rapidly for birds flying within a one-kilometer hemisphere around IdentiFlight towers.[53] Considering there are several bird species classified as endangered in the area, IdentiFlight will assist in reducing the impact of collisions with turbines.

4.0 Social Considerations

Viewshed Impact: Many Great Lakes residents have concerns about the effects of wind turbines on their view of the lakes and are more open to wind energy developments that do not obstruct the viewshed. The State of Michigan recommends turbines to be sited at least 6 miles from the coast to minimize viewshed impacts[54]. The Horizon Offshore Wind Farm is sited 34 miles from shore in the center of Lake Michigan and is therefore not visible from anywhere along the shore. However, to ensure transparency and dialog, information sessions will be held for community members to learn about the project and voice concerns.
Employment Impacts: A 525 MW wind farm can create between 35 and 55 full-time local jobs in Michigan, as well as additional part-time positions and jobs in other states for manufacturing and construction. Beyond this, jobs are created in the service industry to support construction workers who relocate to the area[55].
Fisheries: Fishing is another source of jobs in the Great Lakes region. The wind farm may interfere with some fishing activities[56]. However, it may be possible for the area to be shared with fisheries, which can provide the benefit of fish populations concentrating around the wind turbines[57].
Native Nations: Native Nations with usufructuary rights in Lake Michigan's waters[58] may have concerns about their abilities to continue fishing. The wind farm takes up only a small section of the lake and

should not have a significant impact. However, conversations will be held with Native Nations in the region to understand their concerns and potentially reach an agreement about sharing the space for both fishing and the wind farm.

6.0 Risk Analysis and Fatal Flaws

WiscWind LLC acknowledges the inherent and increased risks associated with Great Lakes offshore wind development, most notably demonstrated by the recent indefinite suspension of Icebreaker Wind pilot project in Lake Erie.[59] As a result, a risk analysis was conducted, and fatal flaws were identified below.

6.1 Leasing and Permitting

A primary risk to the project is the time to obtain a site lease and all permits for construction. In Lake Michigan, public auctions are held for leasing parcels of unpatented bottomlands for offshore wind energy development. Private parties and counties can nominate parcels for lease, subject to certain criteria and procedures.[60] However, effective Nov. 29, 2024, Michigan's utility-scale wind energy and energy storage projects siting process, regulated by Public Act 233, Case No. U-21547A, involves applications to the Michigan Public Service Commission (MPSC) under specified conditions.[61] Initial steps include identifying project areas, evaluating alignment with renewable energy ordinances, and securing land agreements. Formal approval filings detail facility plans, community impact assessments, and compliance with regulations. Permits necessary for the building of Horizon Offshore Wind Farm are listed below in **Table 2**. Delays may arise due to permit acquisition timelines extending beyond the effective date, putting the siting process within jurisdiction of the MPSC.

Table 2. Permits necessary for building a wind farm in Lake Michigan.

Permitting Authority	Permit Type	Description
Environmental Protection Agency (EPA)	Clean Air Act Compliance with Section 328	Monitoring air pollution from outer continental shelf projects.[62]
Federal Aviation Administration (FAA)	Form 7460-1	Ensures turbines do not encroach on navigable airspace.[63]
U.S. Fish and Wildlife Service (USFWS)	Bald and Golden Eagle Protection Act (BGEPA) Permit	Safeguards against impacts on protected species.[64]
USFWS	Migratory Bird Treaty Act (MBTA) Permit, Endangered Species Act (ESA) Permit or Incidental Take Authorization	Mitigates potential impacts on migratory bird species and protects endangered species or authorizes incidental take.[65]
U.S. Coast Guard (USCG)	Private Aid to Navigation (PATON) Authorization	Ensures navigation safety.[66]
USCG	Regulation of offshore wind support vessels	Ensures compliance and safety.[66]
State	**Permit Type**	**Description**
Michigan Department of Environment, Great Lakes, and Energy (EGLE), U.S. Army Corps of Engineers (USACE), Water Resources Division (WRD)	Joint Permit for High Erosion Area Construction	Covers construction activities where land meets water.[67,68]
EGLE	Great Lakes Bottomlands Construction Permit	Ensures minimal impact on Great Lakes Bottomlands.[69]
EGLE	Part 41 Sewerage Systems Permit	Regulates wastewater construction applications.[70]
EGLE	Notice of Coverage (NOC) for Construction Storm Water Runoff under NPDES	Authorization contingent upon Stormwater and Erosion Control (SESC) compliance.[71]

EGLE and USACE	401 Water Quality Certification, Coastal Zone Management Act Section 307 Consistency Certification	Ensures compliance with water quality standards and ensures compliance with coastal management regulations.[72]
Federal Emergency Management Agency (FEMA)	National Flood Insurance Program (NFIP) Compliance	Mandatory for federally backed mortgages within FEMA-mapped floodplains.[73]
MDOT	Alternative Use of Highway Right of Way	For transporting construction equipment and oversized loads.[74]
Municipal	**Permit Type**	**Description**
Port Sheldon Township Planning and Zoning Department	Construction permit	Permit required prior to construction of any structure within the city, such as transmission lines.[75]
Ottawa County	Soil Erosion Permit	Addresses erosion control measures on construction sites.[76]

Note: Data adapted from EPA[21]

6.2 Other Risks

Battery Storage Assumptions: For this project, it was assumed that Consumers Energy would develop the battery storage system instead of WiscWind LLC. According to the JH Campbell Stakeholder Update, the areas at the complex could be used for battery storage development as early as 2024.[40] Thus, it is more favorable for battery storage to be developed in the short-term by Consumers Energy, rather than wait until 2029 for the wind farm to begin construction. WiscWind LLC will therefore receive the economic benefit associated with less grid curtailment and a higher calculated net AEP without directly paying for the capital costs of battery storage.

Weather Related Risks: Ice coverage is an important weather consideration for offshore wind in the Great Lakes. Icing on the blades can result in immense losses in power production and cause potential damage to other systems[77]. One hybrid solution involves utilizing electric heating technology on the critical regions of the turbine blades and water and ice repelling coatings. These coatings would be hydro/ice-phobic surface coatings. They would have ultra-low adhesion strengths in addition to other mechanical properties that reduce ice accretion and surface water runback. The electric heating technology would utilize minimized surface heating to specific critical areas of the turbine blades (e.g. turbine blades leading edges). This hybrid strategy is energy efficient, saving up to 80% energy in comparison to brute-force heating-surface methods.[78] In addition, static and dynamic loads can be induced on the turbine structure due to floating surface ice during ice coverage seasons. The impact of the floating ice can introduce excessive vibrations to turbines and can cause structural damage.[77] Barriers and ice collars will be utilized to reduce this impact. Barriers and collars induce bending in the ice and can break large pieces into smaller, less hazardous pieces.[77] However, Horizon Wind Farm is in an area of Lake Michigan with an annual ice coverage duration of less than 50%.[7]

Social and Environmental Related Risks: The Great Lakes are a source of drinking water in the United States and Canada. Sediment in the Great Lakes contains chemicals and heavy metals that were deposited by industrial pollution and can be toxic to human health. The process of installing wind turbines can cause sediment layers to move around and release these chemicals and heavy metals, consequently allowing them to enter the drinking water supply.[7] In order to prevent this issue, research will be conducted before installation to ensure no areas with toxic chemicals are dredged.

High Capital Cost: Great Lakes offshore wind energy, especially with floating technology, has a higher estimated capital cost than offshore wind developed in other parts of the continental United States due to current regional constraints and the significant need for port upgrades.[7,25] This results in a higher total required investment from sponsors, and is therefore riskier.

6.3 Fatal Flaws

Critical dune area: The point of interconnection (JH Campbell Complex) for this project is located next to a designated Michigan critical dune area[40]. However, transmission lines were planned to avoid this area, and developers will ensure the dunes are protected and preserved throughout the project lifetime.
Space and leasing at the Port of Muskegon: Horizon Offshore Wind Farm assumes smooth working with stakeholders at the Port of Muskegon to ensure there is a quayside of at least 470 feet after upgrading for vessels and the additional assembly barges.[25] Considering there are no current available leases at the Port of Muskegon, WiscWind LLC will work with stakeholders to ensure a sufficient building area and subsequent port lease is obtained in a timely manner.
Milwaukee to Muskegon Ferry Route: The Lake Express Ferry between Milwaukee, WI, and Muskegon, MI comes as close as 4.9 km from Turbine #35 of Horizon Offshore Wind Farm. The turbines will be visible to ferry riders, but this can increase ferry ridership as wind farms can act as a tourist attraction.[80]
Supply Chain Constraints: There are inherent risks associated with port infrastructure and vessels in the Great Lakes as previously described.[7] Horizon Wind Farm will import the components of the Vestas V236 15 MW turbine from Europe, since the current capacity of the US-based Vestas manufacturing facility is being upgraded to support only 4.5 MW turbines so they cannot be transported by land nor manufactured in the US by the time Horizon project begins construction in 2029.[79] The blades, tower parts, and nacelles are currently planned to be shipped via the St. Lawrence Seaway. However, this assumes the locks will be upgraded to support vessels of this length, or innovative methods will be employed to transfer the blades off the ships before they enter the locks.[7] WiscWind LLC will continue to explore the best possible options for shipping the Vestas V236 blades before construction begins.

7.0 Optimization Process

7.1 Site Selection and Transmission Cable Length

To further optimize the site selection for the wind project, another raster overlay was conducted in ArcGIS Pro by WiscWind LLC.[1] An interconnection location had already been chosen at this point, which allowed for replacement of the "port proximity" weighting category with a "distance to interconnection" at the JH Campbell Complex, rather than all available sites. This slightly altered the output of the calculations, but the original site coordinates remained most optimal. However, a new potential location arose approximately 24 km south of the original location. This site had one significant characteristic that led to the decision to relocate, and all others remained suitable across both sites.

The main determinant in the decision was the distance from the new site to the planned interconnection at the JH Campbell Complex. The initial location was 85 km away, but the new site would be only 62.9 km miles away[13]. Moving the site would save approximately $55 million in submarine power cable costs, based on estimates of $2.5 million per kilometer [81]. Additionally, saving on export cable costs allowed the turbines to be spaced farther apart at 6 RD instead of 4 RD to reduce wake losses, while still maintaining a total transmission cable length that was less than the preliminary design.

This new site lies in water that is an average of 80 m deep, whereas the old site was in water 54 m deep at the shallowest. However, the original site had a slight slope, leading to much deeper water in the southeast portion of the turbine layout. Average wind speeds, according to the Global Wind Atlas[82], are approximately 1.5% slower at the new site, an insignificant amount. Additionally, the old site bordered the southern corner of Minnow MOA Special Use Airspace, and this new site is outside of it.[83]

7.2 Turbine Layout

Turbine layouts were manually designed in Furow[8] to minimize wake losses, which were calculated for each layout using the Jensen model with a wake decay constant of 0.04[84] and maximum wake length of 20D. The layouts analyzed were variations of 4 x 6 RD row and turbine spacing and 6 x 6 RD spacing, 7 x 5 versus 5 x 7 turbines, with and without a row offset of 3 RD. These layouts were then tested at row orientations of 210°, 200° and 190° using the Vortex data and **Figure 2** as a reference. It was ultimately found that 7 x 5 turbines with 6 x 6 RD spacing and 200° yielded the lowest wake effect of 10.7%.

8.0 Financial Analysis

8.1 Market Conditions, Power Purchase Agreement, and Revenue

Research into current market conditions has identified several external factors, notably the conflict in Ukraine, that have resulted in heightened market volatility, supply chain disruptions, and escalated project costs.[85] This trend is particularly concerning for capital-intensive sources like offshore wind energy, where key material costs, notably steel, have remained markedly elevated in North America (52% increase between 2019 and 2022).[86] However, initiatives enacted by the Biden administration such as the Inflation Reduction Act (IRA) and the Action Plan For US Offshore Wind Development in the US Atlantic Region seek to make offshore wind more accessible.[87] In addition, Michigan recently passed new clean energy legislation in 2023, which mandates that the state achieve 80% clean energy by 2035 and 100% clean energy by 2040 and allows for the approval of large wind energy projects.[88] Michigan also enacted Public Act 235 in November 2023, expanding renewable energy requirements substantially and adding a clean energy standard. Michigan's renewable portfolio standard (RPS) was increased from 10% in 2015 to 15% in 2021 and will continue 50% by 2030 and 60% by 2035.[89] Notably, Horizon Offshore Wind Farm falls within the purview of these regulations, facilitating easier legislative approval for design plans.

Understanding the trends in Power Purchase Agreement (PPA) prices for solar and wind energy in the Midcontinent Independent System Operator (MISO) market provides valuable insights into the pricing dynamics of renewable energy projects in the region. Solar PPA prices in MISO rose by roughly 55% from 2020 to 2023, whereas wind increased 80% during this time period[90], indicating wind power can be sold at a higher rate. However, due to lack of offshore projects in the United States and in the Great Lakes, there is no verified PPA price for a project like Horizon Wind Farm. One study explored case study PPAs of suggested project proposals using a new project in a region without any offshore wind development (‘the first of kind’), providing sale prices of ~$243/MWh as observed from Block Island Wind Farm.[91] However, this break-even price could be lowered through policies such as federal incentives and the maturity of the wind industry. As such, the study forecasts a significant decline in the cost of offshore wind power, projecting a reduction from the current average of $300/MWh, as seen in the Block Island wind farm's energy cost, which encompasses its subsea cable expenses but excludes federal tax credits. By 2027, the study anticipates that the cost will decrease to approximately $110 per MWh.[91]

For the Horizon Offshore Wind project, securing a PPA stands as a pivotal strategy to ensure revenue stability while mitigating risks stemming from market volatility. Our approach entails seeking out PPAs with established entities within the energy sector, including ensuring reliability and fostering long-term sustainability. Securing a PPA with Consumers Energy, which services the MISO grid, presents a strategic opportunity to not only ensure revenue stability but also to capitalize on the growing demand for renewable energy in the state and region. By partnering with Consumers Energy, we aim to establish a long-term contractual arrangement whereby the electricity generated from our offshore wind farm can help Consumers Energy achieve the goals outlined in their Clean Energy Transformation Plan and can be successfully coupled with a battery storage project developed at the JH Campbell Complex[40].

Consumers Energy can also benefit from this project because through the Michigan Renewable Energy Certificate System (MIRECS), they will receive one REC per MWh of renewable electricity generated through the PPA with Horizon Offshore Wind Farm[92]. This helps the utility meet regulatory targets, diversify its energy portfolio, and enhance its public image through sustainable practices.

The net AEP of the project is 2,204,793 MWh with a degradation rate of 0.5% applied to account for turbine component degradation.[93] Horizon Offshore Wind Farm will sell its energy to Consumers Energy at a price of $123/MWh. This is higher than the $110/MWh projection given above, but other wind farms in Michigan also have higher PPA values. For example, Heritage Energy Stoney Corners Wind Farm has a PPA price of $116/MWh.[94] Therefore, $123/MWh is a competitive price that allows the wind farm to generate revenue, whilst acknowledging the REC benefit Consumers Energy will receive for the electricity generated.[92] Through the MIRECS mentioned above, Consumers Energy could receive up to 2.2 million RECs from the Horizon project that can be sold at an upper limit of $12.46 each.[94] The total revenue generated by Horizon Offshore Wind Farm with this PPA price is therefore $6,580,997,205.

8.2 Initial Capital Cost, Annual Operational Expenditures, and Taxes

Capital and operational expenditures were obtained using unit costs from NREL's 2022 Cost of Wind Energy Review model for floating offshore wind and adjusted to certain specifications of Horizon Offshore Wind Farm such as distance to shore, turbine capacity, wind farm size, and supply chain considerations.[95]

Capital Expenditures (CapEx)

The total initial capital cost for Horizon Offshore Wind Farm is estimated to be $3,067,050,000 and the unit capital cost breakdown is described below:

Turbine: This is estimated to be 25% of the total capital costs at $1487/kW, which is a decrease of $213/kW from the NREL report, because Horizon Offshore Wind Farm will use a larger capacity 15MW turbine as compared to the 12MW model used in the report. As described in the turbine technology section, larger turbines produce a higher capacity and decrease the unit cost, taking advantage of the economies of scale.[16]

Balance of System (BOS): The total BOS capital cost, which includes substructure and foundation, electrical infrastructure, assembly and installation, and development and project management was lowered $19/kW to $3,390/kW. Horizon Wind Farm will have 35 turbines compared to 50 for the NREL model plant, which reduces costs. The model specifies a depth of 739 m off the coast of California, whereas the average depth at Horizon wind farm site is 80 m, a significant reduction. Therefore, substructure and foundation costs were decreased due to use of Aqua Ventus concrete semisubmersible foundations[96], and then further decreased to a final value of $1095/kW to account for lower mooring cable costs. Electrical infrastructure costs increased by $495/kW to $1652/kW due to an export cable length of 62.9 km[13] compared to the 36 km value the report specifies. Costs of assembly and installation were increased to $376/kW, because Horizon wind project uses extra barges at the port for assembly and is located a greater distance from the port, even though less turbines need to be installed. Additionally, it takes longer to ship in only three turbines at a time to be assembled, which increases labor costs. Development and project management costs increased slightly overall by $2/kW to $100/kW, due to the unique siting and development constraints of Great Lakes offshore wind projects that are expected to increase required labor despite the project having less turbines than the model plant.

Soft Cost: Additional costs relating to plant commissioning and decommissioning, contingency, construction finance, and insurance during construction were determined. The overall unit soft costs are $965/kW, which is a decrease of $95/kW from the NREL report. Plant commissioning and decommissioning, as well as construction finance and insurance unit costs were lower overall because of the lower number of turbines, which outweighs impacts of the larger 15 MW turbine capacity due to economies of scale. The unit cost for contingency was increased slightly due to supply chain challenges and risks in the Great Lakes. This was outweighed by the overall decrease in unit costs associated with the smaller number of turbines.

Annual Operational Expenditures (OpEx)

The annual operational expenditures of Horizon Offshore Wind Farm consist of balance of system (BOS) and turbine maintenance costs. These costs take operating labor, maintenance vessel use, and submerged land leases into consideration, among others. Horizon Offshore Wind Farm assumes annual operating expenses of $80/kW, which is less than the $87/kW from NREL's 2022 Cost of Wind Energy Review[95]. The project has fewer turbines, which was expected to decrease the amount of labor and materials needed to support the wind farm, resulting in lower overall operational costs. This value aligns with the $77/kW projected OpEx for floating offshore wind in Lake Michigan in 2035 predicted by NREL[7], but is slightly higher due to an earlier COD of 2033 and therefore less supply chain development. Operational expenses had a 2.5% escalation rate applied for inflation[97].

Taxes

The project is subject to a 21% federal income tax and 6% Michigan corporate income tax.[98,99] Michigan sales tax applied is 6%[99], with an assumed inflation rate of 2.5% throughout the 20-year lifespan of the wind farm.[97]

8.3 Assumptions and Incentives

Starting January 1, 2025, the Inflation Reduction Act (IRA) will transition the energy tax credit into emission based, technology-neutral tax credits, known as Clean Electricity Production Tax Credit (PTC) and Clean Electricity Investment Tax Credit (ITC).[100] Horizon Offshore Wind Farm will claim the new ITC instead of the PTC, as this is recommended for projects with high capital costs[101]. The new incentive will function similarly to the traditional ITC, except major differences are that it is awarded to zero-emissions energy sources, regardless of the technology.[102] Since this project is expected to begin construction in 2029 and have net-zero greenhouse gas emissions, it is eligible for the new Clean Electricity ITC. The base ITC stands at 6%, with the potential to escalate up to 30% if the project aligns with prevailing wage conditions and fulfills apprenticeship criteria.[100] In addition, it was assumed this project is eligible for energy community bonus of 10% because the location of the interconnection is at a coal generation facility expected to retire in 2025.[103,104] Therefore, the project will qualify for a 40% ITC. This tax credit will be applied at Year 0 and be sold at a rate of 94 cents per dollar.[105] Horizon Offshore will also follow the 5-year Modified Accelerated Cost Recovery System (MACRS) to lower the project's income tax liability during the first 6 years.[106]

8.4 Financing Plan

The project assumes a debt fraction of 60%, consistent with NREL 2022 Cost of Wind Energy Review and recommended by SAM.[16,95] The sponsor equity of the capital cost is $1,226,820,000 and the resulting $1,840,230,000 can be financed by the Department of Energy's Loan Programs Office (LPO), J.P. Morgan Chase, and other smaller investment groups[107,108,109]. The loan will be paid through 20 equal principal payments over the 20-year project lifetime. Based on NREL's Annual Technology Baseline: The 2020 Electricity Update[110] and the 10-year treasury trading rate [111], the nominal interest rate was calculated to be 6.8% and converted to a real rate of 4.2% assuming a 2.5% inflation rate.[97] The nominal Weighted Average Cost of Capital (WACC) for the project's financing plan is 6.06%. Horizon Offshore Wind Farm has a Net Present Value (NPV) of $115,946,729, which was calculated by applying the nominal WACC of 6.06% to the yearly real cash flows of the project. The project breaks even after its 13th year and has an Internal Rate of Return (IRR) of 11.0%, making it a worthwhile investment. Finally, wind turbine waste is a significant environmental concern. At Year 20, Horizon wind farm is decommissioned, and turbine components are sold for recycling purposes at a salvage rate of

$45.46/MWh.[112] As a result, the project will generate a total profit of $486,460,181. These numbers are reflected in a cash flow diagram shown in **Figure 5**.

The Levelized Cost of Energy (LCOE) of Horizon Offshore Wind Farm was calculated to be competitive with current floating offshore wind project estimates at $119/MWh. The NREL 2022 Cost of Wind Energy Review currently estimates floating offshore wind to have an LCOE of $145/MWh.[95] A higher average wind speed of 9.17 m/s at the Horizon site in Lake Michigan results in a lower overall LCOE since more electricity is generated. However, the NREL Great Lakes Wind Energy Challenges and Opportunities Assessment also currently estimates floating offshore wind at the Horizon Wind Farm location to have an LCOE between $75/MWh and $129/MWh by 2035 based on current infrastructure.[7] $119/MWh is at the higher end of this range, but the Horizon design is focused on predominantly current infrastructure that mitigates contingency risks to investors, which justifies the need for a higher LCOE.

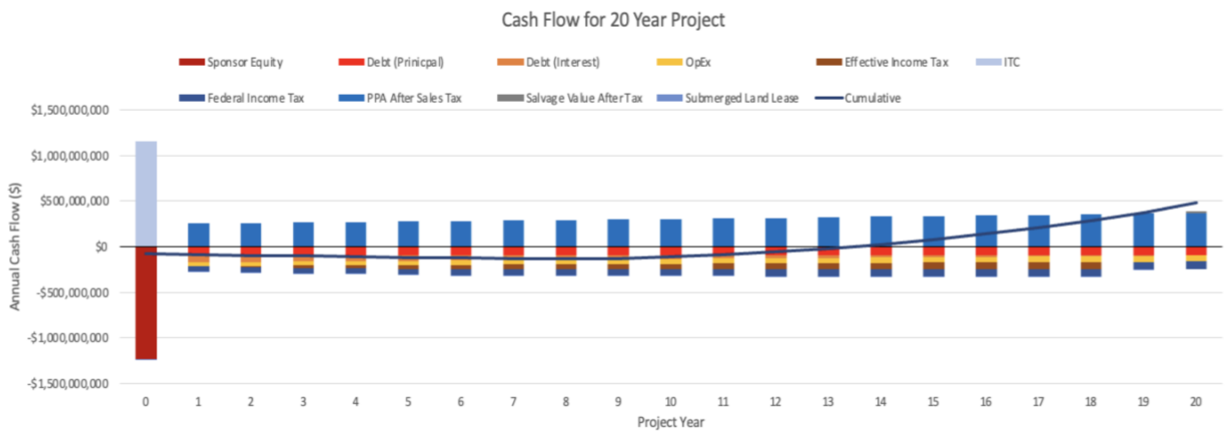

Figure 5. Projected cash flow diagram for 20-year project lifetime.

9.0 Conclusion and Auction Bid

Since Great Lakes offshore wind development is risky and volatile, Horizon Wind Farm heavily relies on proven technology like lithium-ion BESS and proposes solutions that utilize current port and vessel infrastructure. The proposal assumes the minimum upgrades required to develop the project, making it far less risky to Consumers Energy and potential investors even though the LCOE and PPA prices are higher than other offshore wind projects. Therefore, after extensive research, optimization, careful consideration of risks and impact, and a cash-flow analysis, WiscWind LLC has determined the Horizon Offshore Wind Farm to be an attractive and worthwhile investment for sponsors to diversify their energy portfolio. Based on the bid price established in the NREL 2022 Cost of Wind Energy Review[95], developers at WiscWind LLC are prepared to bid a maximum of $88,000,000 for the chosen area in Lake Michigan.

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