CU Boulder Wind Team
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Project Development Final Report

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Table of Contents

Introduction

Offshore wind is becoming prevalent in efforts to decarbonize energy production. With recent wind farm developments off the coasts of U.S., investigations suggest that wind energy in the Great Lakes could become financially feasible and desirable for decarbonizing nearby energy sectors [1]. Our team, BuffWind, used industry standard practices to select and develop a layout of a wind farm in Lake Michigan, conduct a 20-year financial analysis, and outline ancillary benefits of the project.

Site Selection and Energy Estimation

BuffWind selected a site off the coast of West Olive in Lake Michigan. To choose our site, we vetted 14 preliminary locations that avoided critical factors including fishing zones, shipping lanes, protected areas, and military activity. We then created a decision matrix to weigh factors such as wind resource, depth, distance from port, transmission, ice coverage, and community approval, among others. Through this process, we selected our final offshore site with center coordinates at 42.88261°N and 86.7232 °W. The site is 58 km^2 and has 55 turbines with 150 m hub heights.

Wind speeds in Lake Michigan generally increase from the shoreline to the center of each lake. Various data sources document similar trends, with reported speeds ranging from 7.5 to 9.1 m/s at a height of 150 meters. For example, the Global Wind Atlas reported a speed of 9.1 m/s in 2022, while ERA I data spanning from 2006 to 2019 showed an average of 7.5 m/s [2]. A comprehensive analysis of Wind Toolkit Data, sourced from the National Renewable Energy Laboratory's developer network, revealed an average wind speed of 9.59 m/s between the years of 2000 and 2020 [3].

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
00:00-01:00	10.882	10.824	11.165	12.008	11.352	9.545	8.366	7.728	9.271	10.589
01:00-02:00	10.741	10.698	10.952	11.937	11.245	9.520	8.359	7.742	9.190	10.506
02:00-03:00	10.582	10.591	10.806	11.856	11.099	9.511	8.270	7.620	9.010	10.328
03:00-04:00	10.470	10.515	10.689	11.711	10.812	9.388	8.079	7.411	8.901	10.233
04:00-05:00	10.424	10.519	10.647	11.511	10.748	9.227	7.831	7.252	8.754	10.125
05:00-06:00	10.391	10.523	10.612	11.369	10.664	9.193	7.647	7.261	8.641	10.116
06:00-07:00	10.389	10.512	10.577	11.333	10.574	9.157	7.544	7.131	8.524	10.021
07:00-08:00	10.341	10.496	10.558	11.364	10.402	9.075	7.440	7.111	8.551	10.067
08:00-09:00	10.223	10.524	10.503	11.258	10.173	8.846	7.250	7.067	8.496	10.149
09:00-10:00	10.152	10.397	10.178	10.969	9.923	8.478	7.023	6.891	8.314	10.008
10:00-11:00	10.022	10.197	9.882	10.704	9.486	8.103	6.861	6.717	8.130	9.864
11:00-12:00	9.976	10.019	9.678	10.418	9.160	7.852	6.530	6.571	7.977	9.672
12:00-13:00	9.961	9.996	9.579	10.107	8.920	7.496	6.285	6.399	7.820	9.594
13:00-14:00	10.049	10.059	9.554	9.977	8.837	7.271	6.187	6.272	7.634	9.506
14:00-15:00	10.162	10.095	9.575	9.930	8.921	7.289	6.281	6.235	7.583	9.502
15:00-16:00	10.257	10.195	9.643	9.881	8.972	7.411	6.361	6.323	7.582	9.462
16:00-17:00	10.384	10.433	9.790	10.135	9.200	7.629	6.537	6.447	7.650	9.607
17:00-18:00	10.616	10.608	10.033	10.500	9.322	7.899	6.679	6.734	7.908	9.858
18:00-19:00	10.950	10.913	10.471	10.881	9.489	8.064	6.774	6.890	8.274	10.160
19:00-20:00	11.145	11.130	10.827	11.208	9.754	8.393	6.959	7.078	8.628	10.478
20:00-21:00	11.252	11.309	11.092	11.608	10.157	8.483	7.239	7.261	8.908	10.731
21:00-22:00	11.170	11.354	11.373	11.890	10.600	8.845	7.500	7.520	9.099	10.856
22:00-23:00	11.043	11.228	11.515	12.049	11.016	9.220	7.745	7.650	9.321	10.871
23:00-24:00	10.959	11.069	11.487	12.091	11.122	9.440	8.054	7.769	9.421	10.725

Figure 1. Diurnal mean wind speeds from 2000-2020 NREL Wind Toolkit data

Another major factor that we considered in our offshore site selection was existing interconnection infrastructure onshore. The J.H. Campbell power plant, which is currently a 1.56 MW coal plant [4], is located just north of Holland, Michigan. The power plant has an established utility-scale interconnection infrastructure including 345 kV transmission circuits [5] and more. Consumers Energy, the owner of the plant, is currently taking steps to retire the plant in 2025 and use the site for cleaner energy projects, a timeline and focus which closely match those of BuffWind [6]. The power plant also offers a large plot of land that could be used for battery storage, which is critical to operating a utility-scale wind project.

The average depth at the site is 95 m, with a relatively shallow depth gradient ranging from 90 to 100 m. Like many freshwater lakes, Lake Michigan features a weak lakebed composed mostly of soft sand, silt, clay, and soft shale. Also like most lakes, the typical wave height is only 1 m, with up to 3 m waves on windy days. The measured record wave height was 7 m during a severe storm. The temperature at our site ranges between -10 °C and 25 °C, and the average ice coverage during the winter is 30%, with a high variance from year to year.

To guide site selection, BuffWind investigated recent US wind farm failures for insight into challenges and good practices. The Scandia Wind Project, which would have been located near our site, was shut down due to viewshed problems and ecosystem concerns. In contrast, the closest wind turbine is 36 km away from the shore - notably further towards the middle of the lake and therefore is predicted to have a minimal impact on the view [7]. We also plan to implement community outreach and involvement early in the development phase in both the port and interconnection towns to mitigate local environmental concerns. For reference, our site's placement relative to some environmental obstructions is shown in Figure 2.

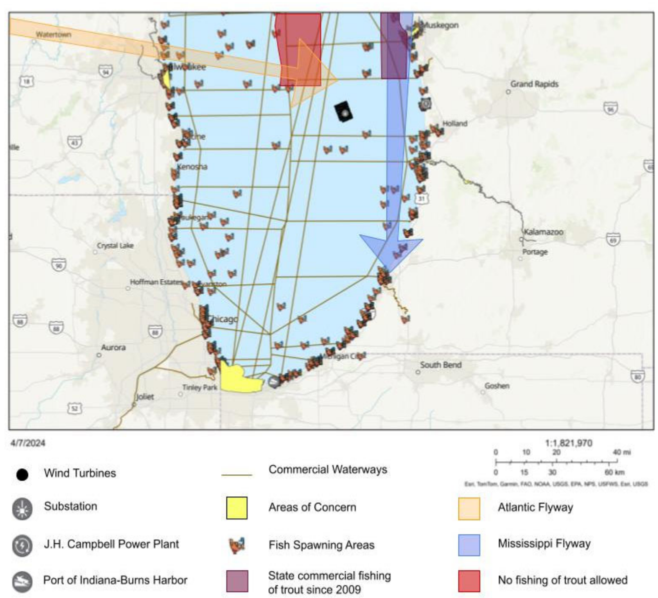

Figure 2. Site layout including existing commercial and environmental considerations.

Turbine and Foundation Selection

Our team decided to use the General Electric 150-6 MW offshore turbine, with an increased hub height to its maximum of 150 meters. This turbine has a rotor diameter of 150 meters, a power density rating of 336 W/m^2, and a rated wind speed of 12 m/s [8]. Although this turbine is optimized for IEC Class I winds, the project site has average wind speeds in the IEC Class II range. Our team could not identify any offshore models optimized for our wind class, but if some were to enter the market closer to our proposed start date, we would explore those options.

To further solidify our decision to use this model, our team compared the output of the System Advisor Model (SAM) with 4 other turbines in a farm sized within 30 MW of our final nameplate capacity. We compared our system to the Vestas 165-9.5 MW and 10 MW turbines, the MHI Vestas 164-8.3 MW turbines, and the Siemens Gamesa 164-8 MW turbines, using a combination of manufacturer specifications and NREL offshore reference specs. None of these options proved to be as economically viable as our current choice, demonstrating its suitability for this project.

Literature surrounding offshore development in the Great Lakes suggests that most turbines larger than 6 MW would require expensive retrofitting on most vessels and available ports [1]. While we recognize that the market is moving towards manufacturing only bigger offshore turbines in the 9 to 15 MW range, these models would require extensive infrastructure upgrades. If this GE turbine were to leave the market before the start of construction, we would consider the next smallest option or partner with a turbine manufacturer to produce a turbine that meets the project's needs.

The foundation that best suits the needs of the turbine, installation, O&M requirements, and the farm location is the Glosten PelaStar tension leg platform (TLP) [9] [10]. This floating foundation offers dockside turbine installation and a small waterline profile that can withstand floating ice loads better than other options. Monopile and jacket foundations are typically used in offshore wind sites are restricted to depths of less than 50 m with a depth of 95 m at the site, a floating foundation is therefore required [11]. Due to the silt and clay composition of the lakebed, driven piles are the best choice for anchoring [12].

Although it would be ideal to have all components manufactured in the United States, the factory currently producing the parts for this specific turbine is located abroad [13]. The Jones Act complicates the import of international turbine components due to vessel restrictions. Our team could not find detailed steps explaining how international cargo is moved between barges when entering the Seaway. However, the Port of Indiana, Burns Harbor frequently receives international shipments. Thus, we are assuming there is a method already in place to ensure imports comply with the Jones Act. Additionally, we have found articles indicating that blades of our length could fit on a barge within the size limits of the Saint Lawrence Seaway [14], possibly eliminating any complications with rail or highway travel. The nacelle and tower are still difficult to ship but can be separated into subcomponents and constructed at the port, so shipping those parts is a lesser concern [15].

Port Selection

BuffWind aims to make decisions that reflect the current market and do not depend on future advancements for project feasibility. While the Ports of Indiana - Burns Harbor, is not currently fit and able to handle the installation of a utility-scale wind farm at its current state, our research leads us to believe that it is the best suited for the job and would require the least retrofitting out of all the ports on Lake Superior and Lake Michigan. The following ports in these lakes were also considered: the Port of Chicago, Ports of Indiana – Burns Harbor, the Port of Milwaukee, and Duluth Seaway Port. Each port was evaluated based on existing crane tonnage, channel depth, size of largest vessel in use, total laydown area and the potential community impacts. Ports of Indiana – Burns Harbor scored highest on a decision matrix based on these factors, leading us to select it.

Port research indicated that an additional 1.5 m must be dredged to meet the draught requirement for TLPs, as all the ports surrounding the lakes have a channel depth of about 9 m. The Ports of Indiana – Burns Harbor has a total laydown area of 74 acres, which is sufficient to construct 6 MW turbines and foundations [16]. Paired with this laydown area, there are additional leasing areas at the port for garages and storage for O&M equipment. While there are four existing 170 MT cranes at the port, the TLP foundation weight is 1200 MT. BuffWind plans to rent heavy lift cranes and install a quay, which would need to support over 10 MT/m^2 [17].

Vessels

BuffWind has strategically avoided jack-up vessels by choosing a foundation type and turbine size that allows for onshore construction and "tugging" out to site. The TLP foundation only requires a bespoke barge in addition to tugboats for installation [18]. Other vessels required for the installation of this farm are environmental-autonomous underwater vessels, vessels with drilling equipment, anchor handling tugs, cable burial vessels, DP vessels, and crew transfer vessels. Lake Michigan currently has all these vessels except wind-farm-specific crew transfer vessels and cable burial vessels. These are usually moderately sized and can be imported via the St. Lawrence Seaway. Additionally, there is a shipyard on the Seaway that is building vessels for offshore wind turbines, from which we anticipate receiving vessels [19]. Crew transfer vessels, towing vessels, and service operation vessels will be needed during operation and maintenance (O&M) [20]. We also anticipate needing icebreakers during winters when there is full ice coverage. Lake Michigan has a fleet of ice breakers already on the lake [21].

Environmental Impacts, Assessments, Permitting, and Mitigation

The construction, operation, and decommissioning of an offshore wind project exert stresses on benthic (bottom-dwelling), pelagic (open-water), and avian communities [22]–the effects of which must be mitigated to protect lake ecology, gain community approval, and comply with state and federal regulations. The most significant environmental risks are addressed by our foundation selection. Since the TLP's minimal mooring infrastructure does not require anchor rodes or fixed-bottom infrastructure, and since our selected site is so deep, wake effects and associated lakebed scouring are reduced [22]. Additionally, the ease of anchor installation reduces the amount of time spent hammering piles which, compared to vibratory piling or reverse circular drilling, results in less sediment suspension and fewer avoidance-inducing noise and pressure waves [22] [23]. Sedimentary disturbances can clog gills, smother benthic organisms, and resuspend contaminants [22]; while acoustic emissions can produce startling, fleeting, and hiding behaviors, mask calls, and cause tissue damage and mortality–particularly for organisms with air-filled organs or middle ears [23]. Ill-effects can be reduced by the establishment of a well-monitored exclusion zone close to the activity, and hammer blow intensity can be gradually increased over the course of 20 minutes or more to allow animals time to leave the vicinity [23].

Unfortunately, dockside turbine assembly increases the risk of invasive species spread from the coast to the project site–where hard-bottom structures can facilitate their proliferation to otherwise inaccessible regions [22]. An estimated 108 different invasive algae, bacteria, invertebrates, fish, plants, protozoa, hydrozoa, and viruses reside in Lake Michigan. As shown in Figure 3, this includes the pervasive and destructive zebra (blue) and quagga (orange) mussels that threaten the health of lake ecosystems upon which communities depend [24] [25]. Although not included in our analysis, preventative measures such as the application of novel non-stick anti-fouling coatings to vessel bottoms can minimize invasive spread without the use of harmful biocides [26] [27].

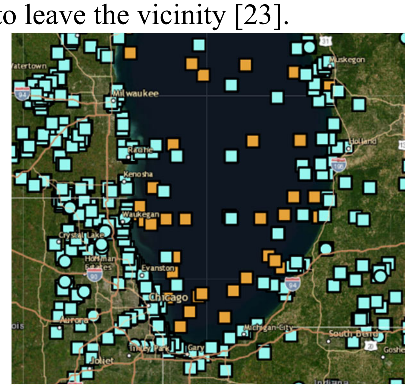

Figure 3. Invasive Mussels Sites

While increased vessel traffic can result in greater disturbances to aquatic species from noise and collisions, the avoidance behavior exhibited in response has been observed to be temporary [23]. Decreasing vessel speeds, avoiding transport through sensitive areas, and halting or reducing activity when species are nearby can further assuage such risks [22].

The J.H. Campbell power plant lies near impaired water contaminated with chlordane, DDT, dioxin, mercury, and polychlorinated biphenyls [28]. Since the trenching required to lay HVAC risks suspending these pollutants and increasing turbidity, it will be important to employ proven control measures like silt curtains and sheet piling or changing cutterhead depth and speed of advance [29]. Similar techniques can be adopted to reduce the impacts of port dredging.

Offshore wind farms can also endanger avian species that experience spatial displacement or collisions. This is of particular concern for the endangered piping plover, tri-colored bat, Indiana bat, and Karner blue butterfly, the threatened northern long-eared bat and red knot, and the monarch butterfly [30]. The migration patterns of these species have been considered but cannot be entirely avoided in any part of Lake Michigan [31]. While preliminary studies have suggested that painting wind turbine blades can increase visibility and reduce avian impacts [32], current FAA regulations do not allow for this modification [33]. Acoustic bird deterrent systems can be mounted to wind turbines, and cameras and radar can be used to detect avian species and trigger turbine shutdown [34] [35]. Site construction can also be planned to avoid migration and breeding seasons and cut-in speeds can be raised to curtail common low wind-speed collisions [36].

Midwestern winter weather can also lead to ice on blades. Passive and active techniques can be used to mitigate this accumulation. Although not included in our analysis, the former typically includes the application of ice-repellent coatings, and the latter generally involves anti- or de-icing techniques [37].

During the predicted 6-24 month [38] decommission period, we will employ circular economic practices to minimize impacts including waste generation and environmental degradation [39]. Nearly all above-ground and submerged infrastructure will be removed, unless it can be reused, to restore the site to pre-project condition [40]. Additionally, novel chemical and other processes will be used where possible to repurpose hard-to-recycle materials like fiberglass from blades [38] [41], seed-mix will be employed for land restoration, and repairs will be made to damaged roads. BuffWind will adhere to all decommissioning requirements defined in property leases. In general, a comprehensive environmental impact assessment and mitigation strategy is key to the success of an offshore wind energy project–along with careful adherence to federal and state regulations.

Table 1. Additional Permitting and Applications [128] [129] [130] [131] [132] [133] [134] [135] [136] [137] [138]

Agency/Act	Associated Permitting/Recommendation
Submerged Land Act, 1953	Compliance. May require permits and leasing for land beneath navigable water.
Michigan Department of Environment, Great Lakes, and Energy (EGLE)	Wetlands Permit (dredging), Submerged Lands Permit (construction activities), and Land/Water Interface – Joint Permit Application.
Indiana Department of Natural Resources	Permits for port upgrade projects
US Army Corps of Engineers	Regional General Permit No. 1
National Environmental Policy Act	Completion of an Environmental Impact Assessment (EIA), a natural resources assessment, etc.
Federal Emergency Management Agency (FEMA)	FEMA Floodplain Assessment
Bureau of Land Management (BLM)	Proposal presentation and stakeholder meetings (Indigenous groups, etc.)
U.S. Environmental Protection Agency	Stormwater Pollution Prevention Plan (SWPP) and Spill Prevention, Control, and Countermeasure (SPCC)
National Oceanic and Atmospheric Administration (NOAA): Endangered Species Act	Compliance
Federal Aviation Administration (FAA)	Meteorological Evaluation Tower (MET) installations, marking between 50 and 200 feet above ground level (AGL), site cannot fall within 3 nautical miles of an airport (compliance), turbines cannot surpass a height of 499 feet (compliance), and compliance with all marking and lighting standards.
State of Michigan	Land use permits
State of Indiana	Land use permits
Union Labor Laws	Compliance
Natural Resources Conservation Service	All conservation easements avoided
Department of Transportation (DOT)	Compliance, cooperation with the local fire Marshall, and all access roads must be approved prior to construction.

Interconnection: J.H. Campbell Generating Facility	
Agency/Act	**Associated Permitting/Action**
Zoning	Compliance with the Township Zoning Act: Act 184 of 1943.
Federal Emergency Management Agency (FEMA)	Compliance with regulations around regulatory floodways and special flood hazard areas (Zone AE and Zone VE).
Conservation Easements	One conservation easement is located in close proximity, but should be avoided.

Port Selection: Port of Indiana-Burns Harbor	
Agency/Act	**Associated Permitting/Action**
Zoning	Compliance with the Specific Use Zoning. Heavy, industrial is permitted in the industrial north.
Federal Emergency Management Agency (FEMA)	Compliance with regulations around regulatory floodways and special flood hazard areas (Zone AE and Zone VE).
Conservation Easements	No conservation easements are located in close proximity.

Energy Production and Layout

The energy generation analysis in this report utilized ERA I data, which as stated in our site description is on the lower side of estimates. Our financial model In SAM also utilized data on the lower end, by only taking Wind Toolkit data from 2014. Integrating Wind Toolkit data from 2000-2020 into the energy generation could increase energy generation by 70.5%, as the average wind speed reported is 9.6 as opposed to 7 m/s. Utilizing ERA I data provides a more conservative estimate.

Modeling the 330 MW farm in FUROW using ERA-Interim reanalysis data [42] gives an annual energy yield of 1236.56 GWh without losses. Our farm consists of 55 6 MW turbines. They are arranged as a 7x8 rectangle without one turbine in the southwest corner and a minimum spacing of 6.66 rotor diameters, or 1000 m [43]. The layout is angled 158° to minimize wake loss and achieve 5.04% wake losses using the Jensen wake loss model. Our site is restricted by shipping lanes to the north, west, and south along with the viewshed from the shore on the east. The levelized cost of energy for our farm has been calculated to be $151/MW, or $0.15/kW. This number is by no means low; however, it is within the range of estimates for present day, and hopefully will drop as technology advances [44].

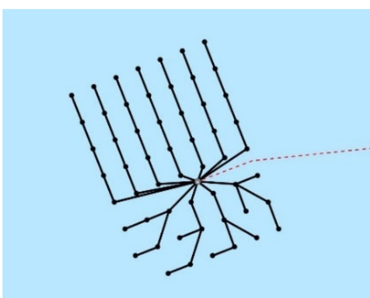

Figure 3. Cable and Turbine Layout

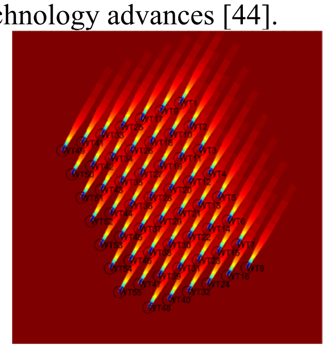

Figure 4. Wake Loss Visual

Interconnection

The electricity generated by the wind farm will be transmitted from the offshore substation to the onshore substation at the J.H. Campbell Generating Plant, which is a coal power plant in Port Sheldon, Michigan. Wind turbines do not generate power at a high enough voltage suitable for transmission, so the voltage is stepped up to a medium collector voltage of 33 kV in the turbine tower. After collection, the offshore substation converts power to a transmission voltage of 132 kV AC, which is typical for this system's transmission distance of 36 km. The subsea AC cables will be trenched and connected to the substation at J.H. Campbell from underground.

J.H. Campbell is currently owned and operated by Consumers Energy, which has slated it to be decommissioned by the end of 2025. Consumers Energy has not announced any plans for the facility other than to use it to generate renewable energy, so BuffWind intends to purchase or lease it for our offshore wind farm through an agreement with Consumers Energy. J.H. Campbell's substation has the capability to receive and distribute electricity at 132 kV and higher, making it an ideal site for connecting to the grid and distributing electricity elsewhere in the Midcontinent Independent System Operator

(MISO) region. Additionally, the rest of the unused space serves BuffWind's goal of hybrid power integration.

Hybrid Site and Generation

BuffWind has explored several options for the hybrid system. First, we considered green hydrogen production via electrolysis, which would use excess electricity from the wind farm to split water into hydrogen and oxygen atoms. Green hydrogen provides a pathway to decarbonize energy-intensive industries including heavy-duty trucking, aviation, steel manufacturing, and ammonia production [45] [46]. Initiatives like the Midwest Alliance for Clean Hydrogen and the proposed $0.60/kg tax incentive through the Inflation Reduction Act demonstrate growing political support for green hydrogen infrastructure [46] [47]. The primary customer to purchase green hydrogen from BuffWind would be Indiana Burns Harbor, which houses the largest blast furnace in the country. Located on the east side of Chicago, Burns Harbor recently completed a successful hydrogen injection trial in Blast Furnace 7 and commissioned a hydrogen pipeline, demonstrating an intent to decarbonize their steel production [48]. Switching to green hydrogen would prevent 4,588,000 tons of CO_2 from being released into the atmosphere per year [45] [49]. However, difficulties such as competition with a nearby Linde gas plant producing green hydrogen, safety issues with transportation, inefficiency of storage, lack of electrolyzer market price information, water rights concerns with natural resource authorities, and the transport distance (about 100 miles along the coast of Lake Michigan), will limit BuffWind's ability to finance green hydrogen production and make its use feasible until green hydration production and transportation technology is more mature [50] [51] [52] [53]. Not only is there danger of hydrogen combusting during transport – hydrogen is the smallest molecule, making it difficult to prevent leakages, and is roughly 20 times more potent than CO_2 over a 100-year time frame [54]. "Tube trailers" could be utilized to transport hydrogen safely but would require large amounts of energy to keep hydrogen gas pressurized [55]. A fiber reinforced polymer (FRP) lined pipeline could be installed to transport hydrogen and prevent embrittlement, but local communities would likely oppose such an action [56]. Existing natural gas pipelines were considered but are all currently in use along the lakeshore [57]. Another issue is supplying sufficient hydrogen to warrant its sale to Burns Harbor. To produce enough hydrogen to meet 5% of Blast Furnace 7's requirements for green steel, 3,805 units would be required, assuming 50 kg of hydrogen is required to produce one ton of steel [45]. Using the $0.60/kg H_2 Production Tax Credit from Section 45V of the Inflation Reduction Act, the cost would be reduced to $4,812,278,625, making hydrogen electrolysis a stretch without a significant investor [58] [59] [60]. If BuffWind maintains carbon dioxide emissions below 0.45 kg CO_2 per kg H_2 and meets the prevailing wage and apprenticeship requirements for Ottawa County, the Investment Tax Credit would increase to $3/kg H_2, reducing the cost to $3,312,347,625 and making it more financially feasible. If, additionally, the wind farm utilizes American-made foundation steel and 20% American-made turbine components, and qualifies as a brownfield or "energy community" site due to the reuse of the J.H. Campbell plant, the Energy Credit of Section 48 would allow the hybrid system to gain a 50% ITC (in place of a 30% ITC) [61] [62]. The project cost would be reduced to $2,062,405,125.

Due to the abundance of solar projects coming online in MISO, and the maturity of the technology, BuffWind considered solar power as a hybrid generation technology. Solar installations are attractive to investors and solar cells are becoming more efficient, with the most recent utility-scale solar hovering around 25% [63]. Solar is also modular and scalable, with a long lifespan [64]. However, single-axis tracking isn't beneficial for floating solar in areas with low irradiance, and it would require additional infrastructure and space on Lake Michigan [65]. Fish spawning areas, local fishing and recreation activities, shipping lanes, and military zones also make this a challenge. While adding a land-based solar array would provide a source of clean energy for Ottawa County and help meet some of the electricity demand that the soon-to-be-decommissioned J.H. Campbell coal plant once accounted for, the lack of significant solar resources at the site, additional required area, and lack of grid support would make it unfeasible.

As of now, a far more attractive option for providing ancillary benefits and maintaining overall grid stability is a large-scale battery system. Batteries provide a source of power when generation from wind and solar plants cannot meet demand [66]. As the percentage of renewable energy increases in the United States, more energy storage options will be necessary to provide enough power for our ever-increasing energetic needs. BuffWind evaluated the financial implications of several utility-scale battery sizes using SAM. A 330 MW system with two hours of capacity was chosen as the optimal site due to its positive net present value and reliable size for frequency control [67]. One hundred seventy-one Tesla MegaPack units will be installed at the site. This system was chosen over 6 alternatives due to its high energy density, real-world performance statistics, extensive testing, and ability to succeed in the current market [68]. Megapacks have been deployed in locations such as Moss Landing, California, U.S., Queensland, Australia, and Geelong with capacities varying from 2 MWh to 300 MWh [69]. The battery site plan is shown in Figure 5.

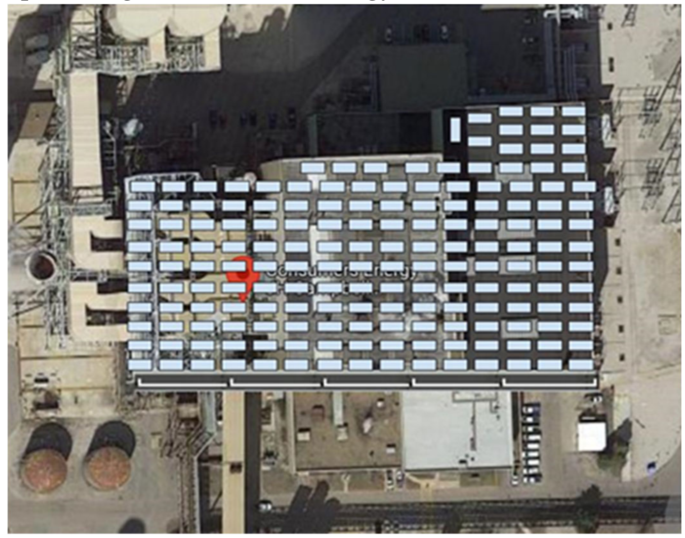

Figure 5. Planned battery site layout.

To size our battery project, BuffWind estimated the energy demand per capita in Ottawa County to resemble Benton Harbor, which is the closest city with readily available load data and is similar in scale to Holland and Grand Haven, Michigan (the two major cities near Ottawa County). BuffWind sourced load data from the Open Energy Data Initiative [70] and scaled the load data to match the population of Ottawa County. The annual generation data was imported from our FUROW model to compare the wind farm's energy generation to the energy demand in Ottawa County. We found that for a typical annual average profile, we can meet 5% of the energy demand for 352/365 days with a battery storage size of 660 MWh, which is 2 hours of the farm's nameplate capacity. Two hours is a good starting point for many utility-scale battery systems for frequency control and contingency (in case of generator failure, outages, etc.) [71]. Unlike solar power, wind energy is available all day and does not need the firm capacity size that a solar farm would require to overcome the energy shoulder.

The team assumed that the battery system will fully charge and discharge, which is poor practice in industry and reduces system longevity. We also made simplifying assumptions that all excess energy would be charged into the battery system, and the required energy would be discharged from the battery system, which may not reflect the complexity of the charge/discharge cycles, frequency control and utility-scale systems.

The plots below, Figure 6 and Figure 7, show the annual average generation and the load, average generation and the load for a specific day, and the required additional battery storage for all the year. For 5% of Ottawa County demand, 330 MW farm, the yearly average demands and loads are shown. The load is typically the highest around the hours 17-20 (5-10 PM), as expected.

As the battery storage size increases, system use can extend beyond frequency regulation to include ramping reserve, arbitrage, and load following capabilities [67]. However, the project cost and the LCOE would increase, making it difficult to sell energy to utility companies. To keep our LCOE low and NPV high, BuffWind determined that a 660 MWh system would provide a robust energy storage system with potential uses beyond frequency control while keeping the system financially feasible.

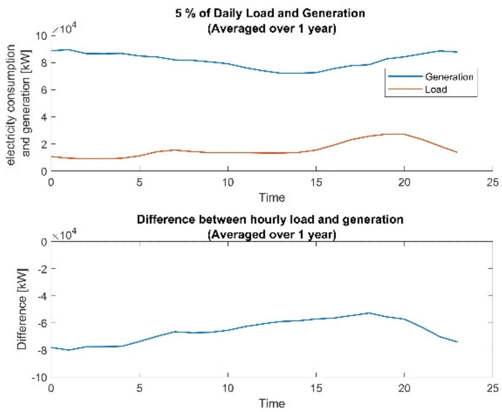

Figure 6. Load, generation, and difference.

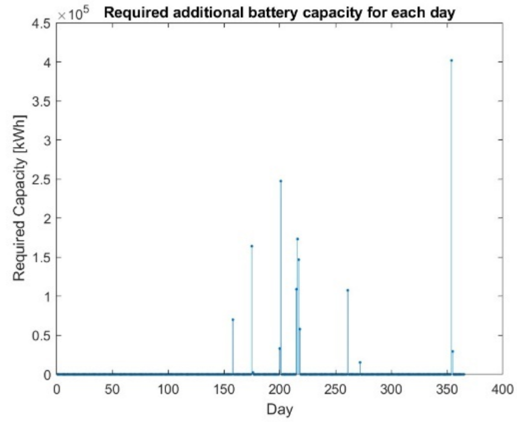

Figure 7. Days we lack storage size.

Stakeholder Evaluation

Based on a review of failed wind project proposals, especially in the Great Lakes region, one of the most significant threats to the implementation of the BuffWind project is opposition from the public and other stakeholders. To evaluate the concerns that could threaten the project, Buff Wind has developed a stakeholder power map (Figure 8) to identify these groups and help us decide how to prioritize stakeholder engagement efforts throughout the project's lifetime. Each stakeholder group is plotted on the x-axis of the map based on its level of support or opposition to the project and on the y-axis according to its level of influence on the outcome of the project. Groups that are in the top left corner, for example, are both highly influential and opposed to the project, meaning that more resources are needed to overcome the risk posed by these. With the U.S. energy goals in mind, we believe that government organizations will be more likely to support the project. The strongest and most threatening opposition will likely come from Ottawa County. If they have a similar population to Ocean County, which blocked Scandia Wind, we expect them to be highly opposed. Evidence of this concern is already materializing via Save the Campbell, a group of citizens that has organized to prevent the closure of the J.H. Campbell coal plant and strongly opposes renewable energy [72]. We plan to begin outreach early to mitigate this and appeal with facts. Ottawa County may not realize that they are in the 85th percentile for cancer in the communities around the J.H. Campbell site, and hopefully showing them the health risks imposed by coal plants will change their opinion, or at least influence it [73].

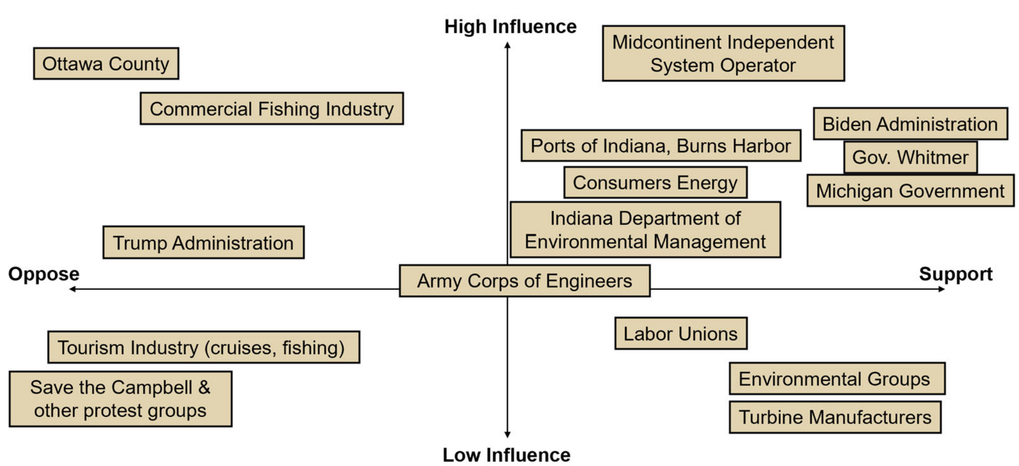

Figure 8. Stakeholder Power Map

Project Timeline

Project timeline estimates are influenced by multiple offshore wind projects currently in construction and academic literature. BuffWind is assuming a worst-case scenario with construction time due to the tow-out days required for TLP installation. With 55 turbines, an estimated construction time of 40 hours for each foundation, and an estimated tow time of 5 days, we are hoping to only need two construction seasons (spring through fall) but are including a third as a buffer [74]. Since the quay side laydown is limited, we are also assuming a sliding shipment schedule, with parts coming in as needed so that we can

2024-2029	2030	2031	2032-2035	2036	2036-2056
All Quarters: Community Outreach, Development	Mobilization at Burns Harbor		Shipments of Parts	Batteries Installed	Project Life Time
Beginning in 2026: Presite surveys, Environmental Evaluations, Legal Review, Auction	Mobilization at J.H. Campbell		Turbine, Foundation, Array Cables and Substation Installation	Commsioning	
Same Evaluations at J.H. Campbell	Any Retrofitting Done at Port.		J.H Campbell Retrofitting	O&M garages built	

Figure 9. Project Timeline, influenced by: [113] [114] [115] [116] [118] [119]

maximize foundation and turbine construction in the laydown space rather than storage. This is why we included multiple cranes and vessels in our JEDI estimate. Lastly, we are considering dredging as separate from construction mobilization because it will ideally be done in conjunction with the State of Indiana. Construction must begin before 2032 to be eligible for the ITC. To have it applied to the battery system as well, battery installation must begin after the farm is installed.

Financial Analysis

Capital Expenditures

Table 2. Capital Expenditures Summary

Capital Expenditures Summary			
Category	**Cost per kW ($/kW)**	**Overall Cost**	**% of Total Cost**
BOS Costs			
Substructure & Foundation	$ 1,739.00	$ 573,870,000.00	28.35%
Electrical Infrastructure	$ 316.00	$ 104,280,000.00	5.15%
Assembly & Installation	$ 432.00	$ 142,560,000.00	7.04%
Ports & Staging	$ 172.00	$ 56,760,000.00	2.80%
Development & Other Costs	$ 394.00	$ 130,020,000.00	6.42%
Engineering & Management	$ 70.00	$ 23,100,000.00	1.14%
Ice Mitigation	$ 100.00	$ 33,000,000.00	1.63%
Plant Retrofit	$ 100.00	$ 33,000,000.00	1.63%
Battery Capital	$ 778.00	$ 256,740,000.00	12.68%
TOTAL	**$ 4,101.00**	**$ 1,353,330,000.00**	**66.85%**
Turbine Component Costs			
Nacelle/Drivetrain	$ 929.60	$ 306,768,306.24	15.15%
Blades	$ 278.77	$ 91,993,397.76	4.54%
Towers	$ 196.71	$ 64,914,696.00	3.21%
TOTAL	**$ 1,405.08**	**$ 463,676,400.00**	**22.90%**
Soft Costs			
Comissioning	$ 40.00	$ 13,200,000.00	0.65%
Construction Finance	$ 166.00	$ 54,780,000.00	2.71%
Construction Insurance	$ 40.00	$ 13,200,000.00	0.65%
Contingency	$ 330.00	$ 108,900,000.00	5.38%
Decommissioning	$ 53.00	$ 17,490,000.00	0.86%
TOTAL	**$ 629.00**	**$ 207,570,000.00**	**10.25%**
TOTAL CAPEX COST	**$ 6,135.08**	**$ 2,024,576,400.00**	

We used NREL's Jobs and Economic Development (JEDI) modeling platform to estimate the initial project costs. The model incorporates parameters such as project specifications, plant characteristics, turbine design, site attributes, substructure design, electrical infrastructure, port characteristics, and vessel deployment details as inputs. JEDI outputs the total capital expenditure (CapEx) costs, encompassing turbine components, BOS expenses, and soft costs.

The total BOS cost was estimated in JEDI to be $3,123/kW. This BOS estimate does not consider some factors specific to the BuffWind wind farm, including the use of the TLP platform. One source estimates the cost of the TLP platform at $1,028 per kW [75], while another suggests $1,688 per kW [76]. A semisubmersible foundation with 5 mooring lines was utilized in JEDI, equating to $1,739/kW, which was deemed adequate based on the literature estimates.

An additional $100 was added to the BOS costs to account for the use of ice cones or other ice protection infrastructure, although we do not have precedent for this number and are primarily adding it as a buffer. Furthermore, since SAM does not model hybrid systems without solar PV, the estimated CapEx for the battery system was disaggregated into a $/kW value and included in the BOS estimate. The chosen battery system, as discussed above, is the Tesla Megapack [68]. Each unit includes a bilateral inverter, power control system, thermal management system, and an AC breaker. All required components are included in the capital cost, which is $256,916,290. Assuming a 20-year warranty costs 10% of the capital cost, this brings the total cost to $283,591,860. This adds an additional $778/kW to the BOS amount. While Consumers Energy will pay for the bulk of the decommissioning of J.H Campbell, it is up to the state and other stakeholders to formulate a plan for reuse and cleaning. We expect to be responsible for the demolition post-clean-up and the grading of the land in preparation for the batteries, totaling to another $100/kW [77] [78].Vessel deployment is an additional input in JEDI, and BuffWind opted for 3 support vessels (including crew transfer vessels), 9 towing vessels, 3 floating barges, 3 array cable installation vessels, and 3 export cable installation vessels for the project. Regarding these vessels, multiples of three were selected to ensure that at least two structures can be constructed simultaneously, along with at least two fully erected tower-foundations being tugged or installed concurrently. With these factors considered, the final BOS estimate is $4,101/kW, yielding a total BOS cost of $1,353,330,000.

The total turbine component cost was estimated using JEDI coupled with SAM. This encompasses the costs of the turbine, nacelle and drivetrain, blades, and towers, and is estimated to be $1,405/kW, yielding a total cost of $463,676,400. Soft costs were also estimated using JEDI (this includes commissioning, construction finance, construction insurance, contingency, and decommissioning). The estimated soft costs are $629.00/kW, which contributes an additional $193,380,000 towards the CapEx costs. The total CapEx is reported to be $2,024,576,400. The breakdown of BOS costs, turbine component costs, and soft costs are summarized in Table 2.

Operational Expenditures

We also employed JEDI to estimate the CapEx costs for the project. An O&M cost of $119/kW was calculated, considering factors such as the site's depth and distance from the port. The cost includes maintenance expenses (covering labor costs, spare parts, and vessels), totaling $82/kW, as well as operating costs, which encompass administrative costs, operating facility expenses, environmental and safety monitoring costs, and insurance, amounting to $37/kW. This estimated O&M expense is relatively high compared to the wind reports provided by NREL. Recent trends indicate that O&M costs for floating platforms are gradually decreasing, due to the increased capability to tow turbines to a port for maintenance, as well as advancements in preventative maintenance technology [79]. Moreover, many reviews suggest that TLPs may be easier to maintain compared to their semisubmersible counterparts [79]. However, despite these considerations, BuffWind has opted for a conservative approach, given uncertainties surrounding ice loading on towers and the potential necessity of renting icebreakers for maintenance. Should tower cones, designed to mitigate ice loading, be available in the market, there could be a requirement for replacement or maintenance. Taking all factors into account, the we adjusted the O&M cost to $145/kW to accommodate the unique challenges posed by offshore freshwater floating turbines.

The yearly operations and maintenance cost for the battery system is $891,860 with a 2% price escalation per year. The estimated $3.4/kW per year for maintenance of the battery system has been factored in, resulting in a final O&M cost of $147/kW with an applied escalation rate of 1% to account for increasing costs with project age. The lifetime O&M costs amount to about 1 billion dollars equating to slightly above one-third of our project's total lifetime costs. Regardless of the battery system inclusion, this O&M total aligns with European averages (25-30%), further solidifying our choice to add buffer [80].

We performed a review of historical yearly leasing prices vs. power purchase agreements (PPAs) and determined our yearly lease payment to be $153/acre, totaling $6.40/kW. This is assumed in the O&M cost.

Power Purchase Agreement

The PPA price used in this calculation was $0.15/kWh. BuffWind referred to the Consumers Energy Rate Book to ascertain the current electricity selling price in the county under consideration. Consumers Energy sells electricity within a range of $0.08/kWh to $0.158/kWh, varying according to demand. [81]. After evaluating current PPA structures in use for wind development, we found that hybrid models (a set percentage of generation set to a cost, with the rest being variable to the market, usually 70-30) are most common in the U.S. across multiple forms of generation, followed by an escalation model [82]. A hybrid model was difficult to model in SAM, so we opted for an escalation model with a set price of $0.11/kWh in year one and an escalation of 2% per year to keep up with trends of recent offshore projects and stay within a range desirable to Consumers Energy [83] [84]. However, this PPA price was not economically viable, requiring us to increase it to the price listed above. This number more accurately reflects the LCOE of our project, but in practice would likely require an extensive review and permission to increase electricity prices from both Consumers Energy and MISO.

Ownership Structure

BuffWind decided to use a PPA in the form of a leveraged partnership flip with debt for the project's financial model. We used SAM to analyze the financial feasibility of the project [85]. We are using an 80-20 project cash split with a 99-1 tax equity split prior to the flip year [86]. These percentages are based on projections for the future market, as investigated by the Norton Rose financial firm in their 2024 renewable energy outlook [87]. Pre-flip, the developer will own 20% of the share of project cash and 1% of tax equity, leaving the remaining 80% of project income and 99% of tax equity to the tax investor(s). This ownership structure will remain the same until the flip occurs at the end of the Internal Rate of Return (IRR) target year, determined to be 3 years for our project. After the IRR target year has been reached, the ownership structure of the project returns will flip, resulting in the developer owning 95% of project cash and 5% tax benefits, leaving the remaining 5% and 95% to the tax investor(s), which is common in the market [86]. Sometimes the tax equity split does not change because the developer does not have a large enough tax appetite, but this model was not viable for BuffWind, so we assume BuffWind has taxable assets. With this current structure in place the investor is in a conservative position and has an IRR of 11.28% and 13.36% at the end of the project. BuffWind's IRR is 13.41%. Financial bodies as large as JPMorgan Chase, Bank of America Corporation, or Wells Fargo are needed for this structure to work because they have a large enough tax appetite to benefit from the tax equity. We are proposing making a deal with Wells Fargo, as they have pledged to invest 500 billion dollars into sustainable financing by 2030 [88]. The remainder of the project will be financed through debt and must meet a DSCR of 1.4 and the PPA price mentioned above. The tenor is expected to last 18 years with an upfront fee of 2.75% of total debt. This financing plan assumes that BuffWind can finance the remaining 20% of the project up front or acquire an equity sponsor.

Taxes, Incentives, and Other Assumptions

The U.S. Federal Government (and many state governments) are providing incentives to encourage the growth of renewable energy and emerging technologies. In particular, the 2022 Inflation Reduction Act (IRA) invested roughly $369 billion of federal funding to support progress toward U.S. energy security and climate change goals [89]. This money is allocated to a variety of programs to provide funding opportunities across a wide range of industries and projects. BuffWind is utilizing the Clean Electricity Investment Tax Credit (IRA § 48E), which includes a 6% tax credit for the qualified investment, as well as an additional 30% if Prevailing Wage & Apprenticeship (PWA) standards are met, and an additional stackable 10% bonus for developing on retired coal plant land (the J.H Campbell site in this case) [90]. The IRA also offers a Clean Electricity Production Tax Credit (IRA § 45Y) of 0.3 cents/kWh or 1.5 cent/kWh if PWA requirements are met, but this was calculated to be much less economically favorable than the ITC for this project [90].

There are also several federal initiatives that are designed to decrease the cost of offshore wind projects in the U.S. that we did not factor into the financial analysis for the BuffWind project because they will have indirect, and therefore difficult to predict, impacts on the costs associated with the project. The first of these initiatives is the Floating Offshore Wind Shot. Created as part of the IRA, this initiative aims to "reduce the cost of floating offshore wind energy by more than 70%, to $45 per MWh by 2035 for deep water sites far from shore" [91]. This will be done by targeting a variety of current challenges in the offshore wind industry, including research and development, strengthening the supply chain, increasing domestic manufacturing of turbines, and improving transmission networks. The next federal initiative worth mentioning is the Port Infrastructure Development Program. This program is overseen by the US Department of Transportation's Maritime Administration, which administers grants to improve port infrastructure in the US [92]. The Bipartisan Infrastructure Law allocated $2.25 million through 2026 to this program, which could be used to improve the Port of Indiana - Burns Harbor to accommodate offshore wind turbines. However, dredging is not planned to take place for the BuffWind until 2030, and it is not guaranteed that BuffWind's application for this grant funding would be approved in the first place.

We also modeled taxes at both the state and federal levels. This includes a federal income tax rate of 21% [93], a State of Michigan income tax rate of 6% [94], and a State of Michigan sales tax rate of 4% [95]. We are assuming a 5-year MACRS depreciation for most of the capital, and a 15-year MACRS rate for the rest.

Net Present Value (NPV)

BuffWind utilized NREL's SAM software [96] to conduct the full financial analysis of the project**.** With all the parameters listed above used as inputs, an NPV of $84.825,976 was calculated for BuffWind, partnered with an NPV of $66,522,960 for our equity partner(s).

Supply Chains Contingencies

The current factory manufacturing our chosen model of turbine is in France [13], and GE is looking to build an offshore facility in New York near the coast of Lake Erie in 2028. The Pelastar specifically has not entered the market yet but is expected to do so with a facility for parts in Maine [97]. If these two factories are completed in time, this would make our project eligible for an additional 10% stackable ITC bonus for 20% turbine parts and 100% steel sourced in the US. This also assumes the rest of the Pelastar can be manufactured at existing factories. These extra funds would eliminate some risks associated with O&M and potentially make hydrogen more attractive to investors. If this incentive was utilized with our current model, the investor NPV would increase to $95,926,816, and BuffWind's NPV to $218,088,384. If the project outlook was this positive to start with, we would expect the capital stack to change. We are not including this in our analysis as it is just a possibility, but it is important to note as the U.S. supply chain continues to mature.

Critical Assumptions

The financial viability of this project is contingent on many pieces falling into place that we cannot account for early in the project. Below are the largest assumptions we are making, broken down by category.

Table 3. Critical Assumptions

Assumption	Description	Level of Concern
Dredging is permitted at Burns Harbor.	The Ports of Indiana - Burns Harbor must be dredged prior to installation to meet drought requirements for tow out.	Medium
BuffWind will be able to purchase the J.H. Campbell plant and use both its water rights and point of interconnection to the electric grid.	Being able to purchase the J.H. Campbell power plant is critical to the success of the project. There could already be a buyer in market that has not been publicly announced, and there is an activist group (Save the Campbell) that is advocating for the local government to purchase and reopen the coal plant.	High
MISO will approve a raise in rates from an average of $.11/kwh to $.15/kwh.	The financial viability of the BuffWind project relies on selling electricity for .15 cents with an escalation rate, which would need to be approved by MISO.	High
Large firms have a big enough tax appetite to invest in the project, and IRA credits are transferable.	There needs to be investment partners for this plan to work. While the idea of transferability of tax credits is being discussed in industry, it is not specifically mentioned in the IRA.	High
There will still be 6 MW turbines on the market in 2032.	Turbine manufacturers are continuing to increase the size of their turbines, so there is some concern that there will no longer be any 6 MW turbines on the market at the time of project construction.	Medium
Pelastar foundations will be commercially available by 2032.	These foundations are ideal for the project because of their capacity for ice mitigation, which would significantly reduce O&M costs. They are not currently on the market in the US, but there is a proposed production facility in Maine.	Medium
The project meets the IRA PWA requirements.	The financial viability of the BuffWind project relies on receiving the full 30% ITC base.	High
Project begins construction before 2032.	Construction must begin in 2032 to be eligible for the ITC.	High
The contingencies added to the O&M and BOS costs do not exceed the estimates used by BuffWind.	The contingencies used in the financial models for these costs were based on numbers not specifically related to wind projects due to the novelty of floating offshore wind and lack of benchmarking data. These estimates, while conservative, could increase the overall cost of the project and affect its financial viability.	Medium
BuffWind receives all necessary permits.	The project must have all permits before construction can begin.	High

Optimization Process

BuffWind has taken measures to optimize the site design within technological limits. The first is comparing capacity factors of multiple turbine models at our location, which is explored and justified in our midyear report. After adding 90 MW of nameplate capacity to the farm, we compared the wake losses of a grid format to the money lost if we expanded the lease area to minimized wake losses. This was deemed negligible, and a grid format was chosen to make the array lay less complicated and hence less expensive. The angle of the turbines vs. NPV was also graphically evaluated, and an angle of 158 degrees southwest was ultimately chosen. BuffWind ran over 100 SAM iterations, tracking a variety of parameters, to conduct a sensitivity analysis. These include O&M costs, PPA price, O&M escalation rate, PPA escalation rate, turbine quantity, turbine model, BOP costs, and flip percentages. While all these parameters cannot necessarily be optimized since they're heavily market dependent, we wanted to see which ones had the largest effect on our final NPV and IRR. The PPA, BOS, and flip percentages were determined to heavily impact the outcome, whereas dropping or adding a turbine and changing O&M costs did not influence the outcome very much. A few of the charts we analyzed are shown below in Figure 10 and Figure 11. During Phase 2, BuffWind utilized multiple decision matrices to make the best choice of port, site location, and technology. These matrices were referenced throughout our decision process in Phase 3, but the top choices never changed.

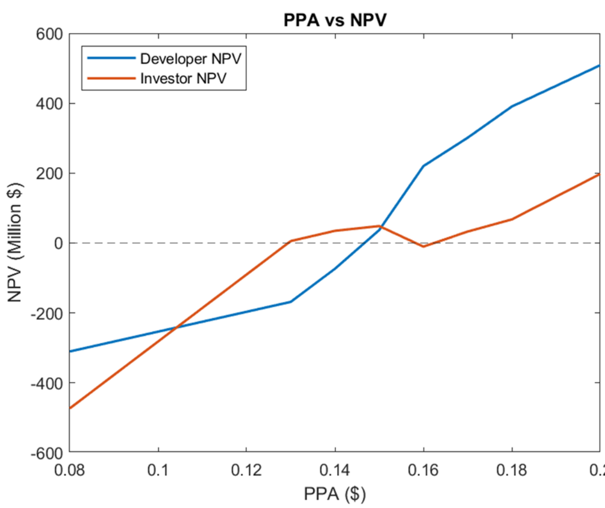

Figure 10. PPA vs. NPV Sensitivity

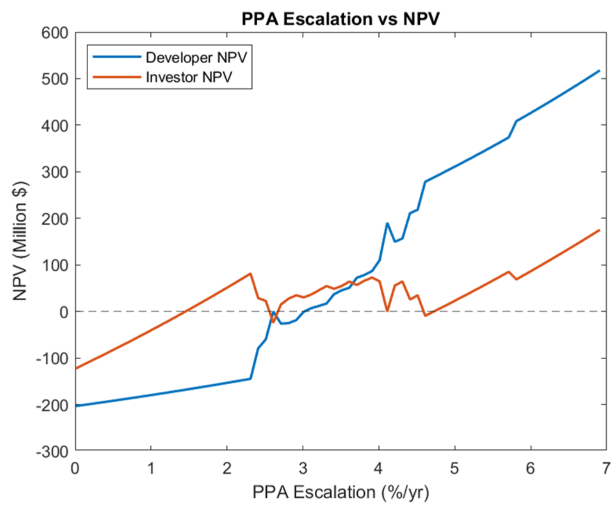

Figure 11. PPA Escalation vs. NPV Sensitivity

Bid for Lease

BuffWind has evaluated recent winning bids in the U.S. In the Northern Atlantic the average wind speeds at recently leased areas were in the 8-9.5 m/s range, and the average winning price per acre was about $8,830 [98]. However, in the Southern Atlantic the average speed is 7.5 m/s, and the average price per acre for the winning bids was $2,865 [99]. Lastly, the California wind speeds at each leasing location range from 7-9 m/s, yet the average price per acre for the winning bids was around $2,059 [100]. The bottomlands and waters of the Great Lakes in the proposed site location are managed by the Michigan Department of Environment, Great Lakes, and Energy (EGLE), from which a Great Lakes Submerged Lands Construction Permit and a Conveyance would need to be obtained, so we expect to coordinate with them [101] [102]. Additionally, we would need to coordinate with MISO (as stated previously) to comply with all FERC requirements. Beyond these bodies, the exact process for an auction is unknown. The levelized cost of energy and nominal NPV per MW were considered for our bid and evaluated against the recent auctions. Following the steps outlined in the Guidehouse model [103] , we are moving forward with a bid proposal of $2,447 per acre. This number is consistent with prices in the market and a reflection of our NPV.

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