New York State Great Lakes Wind Energy Feasibility Study: Substructure Recommendations

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NEW YORK STATE | NYSERDA

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New York State Great Lakes Wind Energy Feasibility Study: Substructure Recommendations

Final Report

Prepared for:

New York State Energy Research and Development Authority

Albany, NY

Prepared by:

National Renewable Energy Laboratory (NREL)

Golden, CO

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Abstract

The Great Lakes Wind Feasibility Study investigates the feasibility of adding wind generated renewable energy projects to the New York State waters of Lake Erie and Lake Ontario. The study examines myriad issues, including environmental, maritime, economic, and social implications of wind energy areas in these bodies of freshwater and the potential contributions of these projects to the State's renewable energy portfolio and decarbonization goals under the New York State Climate Act.

The study, which was prepared in response to the New York Public Service Commission Order Case 15-E-0302, presents research conducted over an 18-month period. Twelve technical reports were produced in describing the key investigations while the overall feasibility study presents a summary and synthesis of all twelve relevant topics. This technical report offers the data modeling and scientific research collected to support and ascertain Great Lakes Wind feasibility to New York State.

To further inform the study in 2021, NYSERDA conducted four public webinars and a dedicated public feedback session via webinar, to collect verbal and written comments. Continuous communication with stakeholders was available through greatlakeswind@nyserda.ny.gov NYSERDA's dedicated study email address. Additionally, NYSERDA and circulated print advertisements in the counties adjacent to both Lake Erie and Lake Ontario as to collect and incorporate stakeholder input to the various topics covered by the feasibility study.

Keywords

Great Lakes, offshore wind, floating offshore wind substructures, fixed-bottom offshore wind

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Acronyms and Abbreviations

DEA	drag embedment anchor
DLC	design load case
GBF	gravity-base foundation
GLW	Great Lakes Wind
HAWC2	Horizontal Axis Wind turbine simulation Code 2nd generation
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
MN	meganewtons
MW	megawatts
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NTNU	Norwegian University of Science and Technology
NYSERDA	New York State Energy Research and Development Authority
SAMCoT	Sustainable Arctic Marine and Coastal Technology
SAMS	Simulator for Arctic Marine Structures
TLP	tension-leg platform
U.S.	United States
VLA	vertical load anchor

Executive Summary

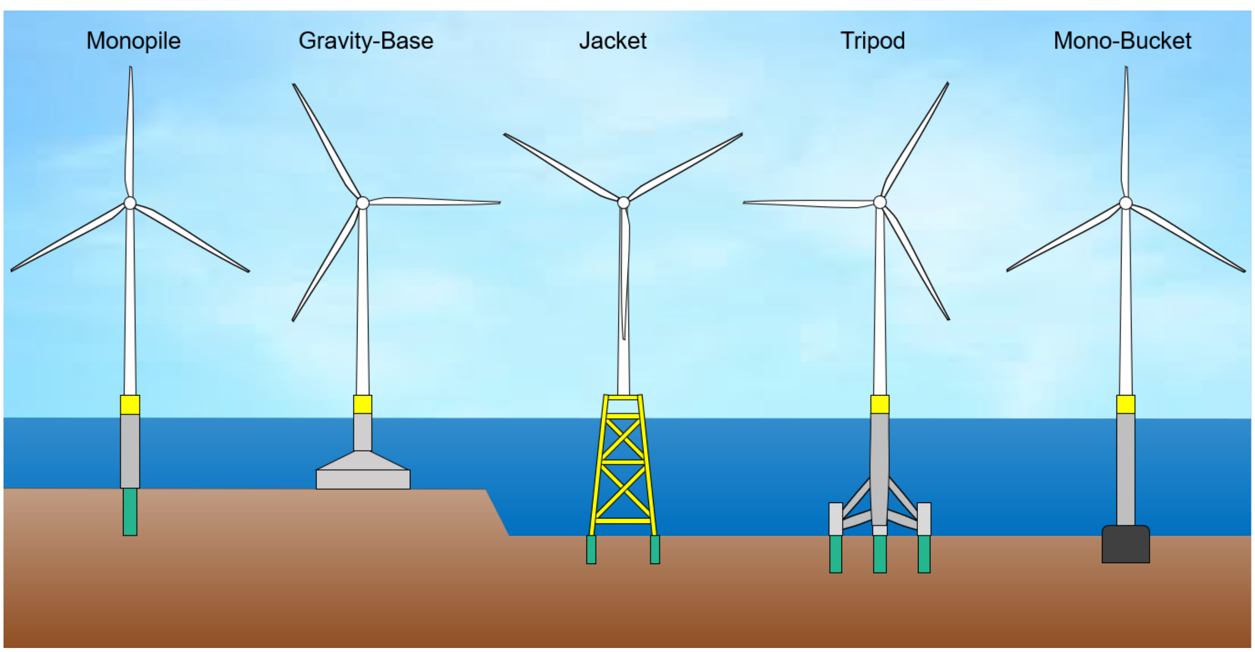
This report assesses the feasibility of various fixed-bottom and floating wind substructure technologies in the Great Lakes. It details the most prominent design-driving technology factors, including ice, soil conditions, and supply-chain limitations, and how each would affect the design of a fixed-bottom or floating substructure in the Great Lakes. The presence of ice in the Great Lakes creates the potential for significantly higher loads on a structure due to the size and frequency of ice floes and ridges. The lakebed soils of the Great Lakes are soft, and the depth to bedrock is shallow, relative to other development areas of the world. The dimensions of the locks of the St. Lawrence River are too narrow for most conventional installation vessels to navigate through, and the ports and cranes along the Lakes are currently not large enough to support wind farm development. A taxonomy of conventional fixed-bottom and floating substructures is detailed, and each substructure is qualitatively assessed for its feasibility in the Great Lakes based on installation ability, lakebed compatibility, ice-structure interaction, local manufacturability, system cost, and technology readiness. The most feasible fixed-bottom substructures for the Great Lakes are gravity-base foundations, tripods, and monobuckets, and the most feasible floating substructures for the Great Lakes are hybrid substructures, like the TetraSpar, or tension-leg platforms. However, certain adaptations of these conventional substructures in response to the unique conditions of the Great Lakes would likely be the most feasible substructures. Lastly, an evaluation of developed ice modeling tools is provided for both fixed-bottom and floating structures, where most methods and tools are used for ice interactions with fixed-bottom structures. In general, these tools cannot accurately model ice ridges, which are the ice forms that produce the most extreme loads on structures and would be the dominant influence on the design of a substructure.

PART I. Fixed-Bottom Substructure Recommendations

1 Fixed-Bottom Design Challenges and Drivers

By the end of 2021, over 50,000 megawatts (MW) of offshore wind turbines had been installed globally, and all but approximately 123 MW of this capacity is classified as fixed-bottom installations. Fixed-bottom support structures provide a rigid connection between the turbine and the lakebed and are generally the most economical and logical option for support structures in water depths less than 60 meters (Musial et al. 2021). European countries have industrialized the manufacturing and installation of fixed-bottom substructures to provide the cheapest and strongest substructure for their given environment. Common fixed-bottom substructures used in the industry, which are later evaluated for their feasibility in the Great Lakes, are shown in Figure 1.

Figure 1. Fixed-Bottom Substructures Considered



Great Lakes Wind (GLW) would likely deploy similar types of fixed-bottom substructures as Figure 1, but the designs would require modifications to accommodate the physical and logistical conditions of the Great Lakes. Primary examples of these conditions include the presence of freshwater ice, differing soil properties and strengths, and the restricted availability of heavy lift vessels for installation.

The objective of this report is to evaluate the primary design challenges of fixed-bottom substructures in the Great Lakes and determine the feasibility of existing, ocean-based fixed-bottom substructures in response to those design challenges in the Great Lakes. These findings will hopefully lead to new fixed-bottom substructure adaptations that are optimized for a Great Lakes environment. Many of these adaptations have not yet been developed but are already in their early design phases and can be implemented with today's engineering tools. This report is limited to the New York State portions of Lake Erie and Lake Ontario, but one of the key findings of the study is that projects in Lake Erie will likely need to use fixed-bottom support structures due to its relatively shallow depth, whereas projects in Lake Ontario will likely use floating support structures. Therefore, the following fixed-bottom analysis is focused on Lake Erie.

To evaluate the effects of the physical and logistical design challenges of the Great Lakes, a representative support structure design is used in the engineering loads analysis of the Great Lakes. The engineering model consists of the NREL 5 MW reference wind turbine and a general, cylindrical, steel monopile substructure in a water depth of 30 meters. The NREL 5 MW reference wind turbine is considered an accurate approximation for the scale and loading of a wind turbine that may be selected for GLW due to its open-source accessibility and its size, which is close to the 6 MW GE Cypress wind reference turbine that is described later. It should not be assumed that the monopile is the best choice of fixed-bottom substructure for Lake Erie but is used here as a surrogate to demonstrate relevant lake conditions. The representative monopile substructure has a 6-meter diameter (which is the bottom diameter of the turbine tower), a length of 50 meters, and a weight of 600 tons. This model was used to quantify and qualify the changes in environmental loads due to freshwater ice, the changes in soil conditions of eastern Lake Erie, and changes in supply-chain requirements for GLW. An engineering model of the GE commercial 6 MW turbine, referenced in other parts of this study, was not available due to the confidentiality of the design properties, and it was beyond the scope of this report to create a new model.

1.1 Ice Loads

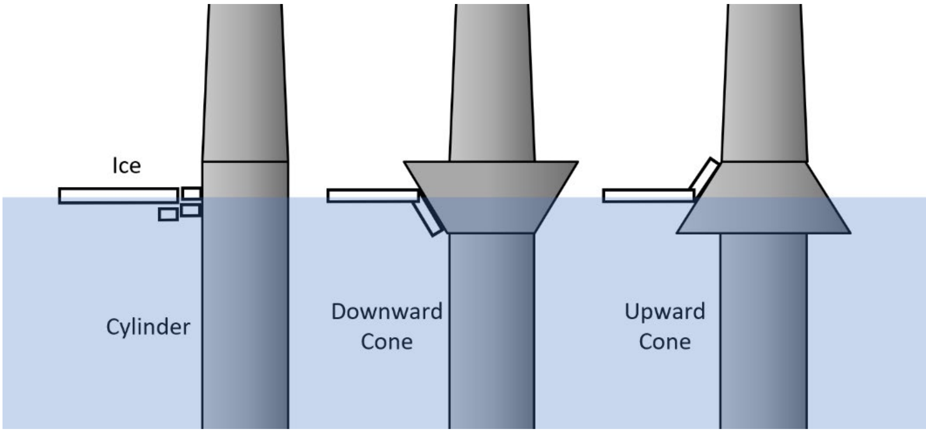
Ice is likely to exert the highest loads on a structure in the Great Lakes and be the most design-driving factor for GLW technologies. Lake Erie experiences a larger area and a longer duration of ice cover compared to Lake Ontario. As explained in New York State Great Lakes Wind Energy Feasibility Study: Evaluation of Site Conditions (NYSERDA 2022a) the average annual duration of ice cover is 7–10 weeks for the majority of Lake Erie and 1–2 weeks for Lake Ontario. For fixed-bottom substructures in Lake Erie, this means that ice floes, or sheets of floating ice, will have a consistent presence during the winter months. Ice ridges, which are large aggregations of broken and refrozen ice sheets that can have high-keel depths, can be present in Lake Erie during the winter months and can produce large loads on a structure. Determining the magnitude of extreme ice ridge loads in potential GLW development zones is the primary challenge for engineering the support structure. The greatest uncertainty is the estimation of ice ridge thickness and keel depth, which will vary based on the specific lake, the distance from shore, and the weather model used. Other variables may include substructure profile, depth of ice cone, and the location of the wind turbine within the wind farm.

The force that ice exerts on a structure is directly correlated to the force required to break the ice as it moves past a structure. This breaking force can vary significantly depending on the mode in which the ice fails. Common modes of failure for ice include crushing, splitting, bending, and buckling. The specific failure mode that occurs is determined by the properties and characteristics of the ice and the geometry of the structure. These characteristics primarily include the ice thickness, ice velocity, structure diameter, and angle of incidence of ice floe impact. The crushing ice load on a structure, which is the force required to break a sheet of ice in crushing, can be an order of magnitude higher than the flexural ice load, which is the force required to break a sheet of ice in bending. Therefore, it is important to understand the situational conditions of ice in relation to offshore structures.

There are mitigation methods to reduce the ice load on the structure and induce a more benign ice failure mode. The simplest mitigation method is to ensure the waterline profile of the structure is as slender as possible, to avoid the large loads that result from higher bearing areas in wider substructures, or from ice jamming in multiple-legged structures, such as jackets, when ice piles up between the legs. Most offshore wind structures that encounter ice loads, especially in the Baltic Sea, are also outfitted with an ice cone, as shown in Figure 2, to shift the failure mode from crushing (left side of Figure 2) to a bending mode of failure (center and right side of Figure 2), which significantly reduces the loads on the structure.

Figure 2. Crushing Ice Failure Profiles

Failure induced in vertical profiles (left) and flexural failure induced in downward sloping (middle) and upward sloping (right).



The downward sloping ice cones are preferred and are the most commonly used. While both upward and downward cones provide the needed shift to a flexural failure mode, the downward cone provides the dual benefit of creating a service platform for workers accessing the turbine system. In the Great Lakes, because the summer wave heights are much lower than the open ocean, this platform may be lower and could potentially eliminate the need for an additional service platform at a higher elevation. This can simplify the tower design and offsets the additional capital expenses of the ice cone.

To quantify the effect of the extreme ice loads of Lake Erie and compare against other environmental loads in the region, the representative NREL 5 MW reference turbine and substructure was analyzed. The extreme ice loads on a fixed-bottom support structure in Lake Erie will most likely be caused by contact with ice ridges. In Lake Ontario, however, ice floes and ridges will be less prevalent, especially in areas farther from shore where GLW might be placed, because Lake Ontario ice cover is less than Lake Erie ice cover. As stated in New York State Energy Research and Development Authority (NYSERDA). 2022. "New York State Great Lakes Wind Energy Feasibility Study: Evaluation of Site Conditions (NYSERDA 2022a), the characteristics of ice ridges in the Great Lakes are highly uncertain and detailed information about ice thicknesses is sparse. A detailed analysis of a full ice ridge load on a support structure is out of scope for this report. However, there are methods that can be used to roughly estimate ice ridge loads for a given ridge size.

Ice ridge loads on a structure can be estimated using Equation (1) (International Organization for Standardization 2010), where F_R is the total horizontal force caused by a first-year ridge, F_C is the force component due to the consolidated layer of the ridge, and F_K is the force component due to the ridge keel.

Equation 1.

$$\boldsymbol{F_R = F_C + F_K}$$

F_C is calculated the same way as any other general thin, rafted ice load. Thin, rafted ice loads are estimated using a proper ice load calculation method that is dependent upon the specific situational conditions of the ice-structure interaction. There are convenient tools available in industry that utilize various ice load calculation methods to model various ice failure modes, which are explain more in Section 3. IceDyn, which is a module that is part of NREL's coupled aero-elastic-servo-hydro OpenFAST simulation tool, is capable of calculating ice loads using ice cones that fail the ice sheets in bending.

The extreme ice loads on the NREL 5 MW representative design were estimated using the available ice load calculation methods. The bending failure method in IceDyn is used to calculate the ice load contribution from the consolidated layer, F_C, of an ice ridge. This method utilizes extreme ice parameters of structure diameter, ice velocity, and ice thickness distinctive of eastern Lake Erie to calculate the consolidated layer ice load. The second component, F_K, is estimated using Equation (2) (International Organization for Standardization 2010), where μ_ϕ is the passive pressure coefficient, h_k is the vertical distance between the base of the consolidated layer and the base of the keel, c is the apparent keel cohesion, w is the width of the structure, and γ_e is the effective buoyancy which is dependent on the porosity.

Equation 2.

$$\boldsymbol{F_K = \mu_\phi h_k w \left(\frac{h_k \mu_\phi \gamma_e}{2} + 2c\right)\left(1 + \frac{h_k}{6w}\right)}$$

The specifics of these ice ridge parameters can be found in the ISO 19906 standards.

Specific ice ridge data are difficult to find or may not exist for this region. Since this analysis is only determining the relative magnitude of these extreme ice loads, conservative estimates of these ice ridge parameters for eastern Lake Erie are used and are shown in Table 1. More details on ice ridge anatomy can be found in New York State Energy Research and Development Authority (NYSERDA). 2022. "New York State Great Lakes Wind Energy Feasibility Study: Evaluation of Site Conditions (NYSERDA 2022a).

Using these two methods to calculate F_C and F_K, the total maximum extreme ice load on a structure in eastern Lake Erie can now be estimated and compared to the existing maximum extreme environmental loads. The extreme conditions of the region and relevant model-specific parameters are also listed in Table 1.

Table 1. Eastern Lake Erie Extreme Environmental Modeling Conditions

Parameter	Value	Unit
Water Depth	30	m
Structure Diameter	6	m
Ice Velocity	0.2	m/s
Level Ice Thickness	0.7	m
Water Density	1000	kg/m3
Ice Density	910	kg/m3
Passive Pressure Coefficient (μ_ϕ)	1	-
Keel Depth (h_k)	20	m
Keel Cohesion (c)	6	kPa
Keel Porosity (e)	0.25	-
Effective Buoyancy (γ_e)	0.66	kN/m3
Rated Wind Speed	11.4	m/s
Significant Wave Height	5.5	m
Dominant Wave Period	9.5	s

The specifics of this ice ridge keel load calculation (F_K) can be found in the ISO 19906 standards. Keel load estimates are a function of the ice rubble internal friction (ϕ), which is used to calculate the passive pressure coefficient (μ_ϕ), and ice rubble cohesion (c). The ice rubble internal angle of friction is assumed to be zero degrees and the keel cohesion is conservatively set at 6 kPa based on guidance from ISO 19906. The effective buoyancy is a function of the local water and ice densities and the keel porosity (e), where the keel porosity is assumed to be 25% based on guidance from ISO 19906. Lastly, keel depths are generally difficult to measure and can sometimes be a function of the consolidated layer thickness, but a conservative value of 20 meters was chosen based on existing data and literature from other Lake Erie studies (Allyn and Croasdale 2016). Ice loads are not dependent directly on water depth, but rather the keel depth, which cannot be larger than the water depth.

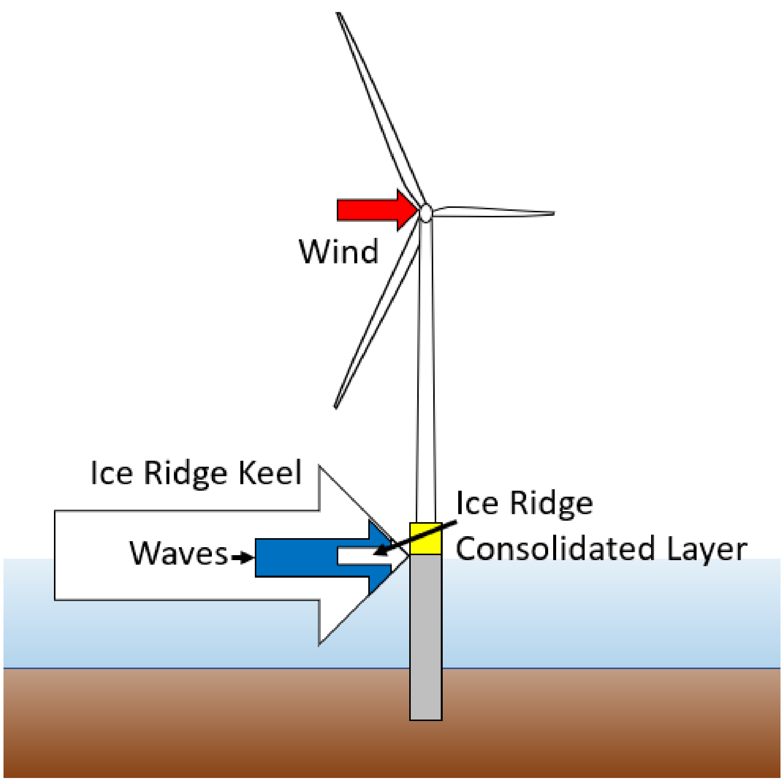
To compare these ice loads to other environmental loads, the NREL 5 MW representative design was simulated in OpenFAST without the presence of ice to calculate the aerodynamic and hydrodynamic loads on the support structure. The resulting loads and overturning moments are tabulated in Table 2. A graphic to show the relative magnitudes of the loads on the representative design is shown in Figure 3.

Table 2. Extreme Environmental Load Comparison Chart

	Lake Erie Representative Design	Atlantic Ocean Representative Design
Consolidated Layer Ice Force (MN)	0.7	0
Consolidated Layer Ice Bending Moment (MN-m)	21.0	0
Keel Ice Force (MN)	3.5	0
Keel Ice Bending Moment (MN-m)	105.0	0
Aerodynamic Force (MN)	0.8	0.8
Aerodynamic Bending Moment (MN-m)	96.0	96.0
Hydrodynamic Force (MN)	1.5	1.9
Hydrodynamic Bending Moment (MN-m)	45.0	57.0
Total Horizontal Force without ice (MN)	2.3	2.7
Total Bending Moment without ice (MN-m)	141.0	153.0
Total Horizontal Force with ice (MN)	5.0	N/A
Total Bending Moment with ice (MN-m)	222.0	N/A

Figure 3. Relative Magnitudes of the Horizontal Load

The arrows in the figure represent the relative magnitudes of the horizontal load and base bending moment for wind, waves, and ice on the representative design.



The maximum wind thrust force of the GLW representative design is assumed to be the rated wind thrust force (0.8 MN) of the NREL 5 MW turbine with rated wind speed of 11.4 m/s. The wind overturning moment is assumed to be the product of the wind thrust force and the moment arm to the lakebed, which is calculated as the sum of the hub height and the water depth. The extreme hydrodynamic loads of the representative design, without the presence of ice, are calculated using the HydroDyn module of OpenFAST, which simulates a maximum horizontal force of 1.5 MN using the extreme irregular wave spectrum data provided in Table 1, characteristic of average maximum extreme eastern Lake Erie conditions (NOAA 2021). The subsequent wave overturning moment is calculated as the product of this hydrodynamic force and the depth to the lakebed.

For comparison, the representative design is assumed to have a counterpart deployed in the Atlantic Ocean, where there is no ice. The maximum wind thrust force on this counterpart is assumed to be the same wind thrust force on the representative design, which is the rated wind thrust force of 0.8 MN. The maximum hydrodynamic force can be calculated using extreme values characteristic of the Atlantic Ocean, with a maximum significant wave height of 6.15 meters and a dominant wave period of 10.53 seconds (NOAA 2021), resulting in a maximum horizontal force of 1.9 MN. This hydrodynamic force is larger than the maximum hydrodynamic force simulated in eastern Lake Erie, which can be expected, but does not make up for the extra force on the GLW support structure when exposed to extreme ice conditions.

The resulting extreme ice ridge load on the representative design was calculated to be 4.2 N, with 0.7 N as a result of the consolidated layer and 3.5 N as a result of the ridge keel. A comparison of this estimated maximum ice ridge load can be made to the ice ridge load calculated by the Lake Erie Energy Development Corporation (LEEDCo), which is developing fixed-bottom support structures in western Lake Erie. Extreme ice conditions will vary between western and eastern Lake Erie; however, they derived a 50-year design ice load of 7.4 MN on a structure with a 60-degree ice cone and a waterline substructure diameter of 7.5 meters, based on an extreme ice ridge thickness of 1.1 meters and an ice keel depth of 16 meters. They also derived a maximum load of 3.5 MN on a 60-degree upward-sloped cone and a maximum load of 1.5 MN on a 60-degree downward-sloped cone from a 1-meter thick level ice sheet with the same structure diameter, without ice ridge considerations (Allyn and Croasdale 2016). Using this study, the maximum ice ridge load is larger in western Lake Erie compared to the estimations calculated above for eastern Lake Erie primarily due to differences in extreme ice properties between the two ends of the lake. Ice thickness has a major contribution to the overall ice load. The consolidated layer in western Lake Erie is assumed to have a thickness of 1.1 meters, whereas the maximum ice thickness in eastern Lake Erie is assumed to be 0.7 meters. There are a plethora of factors that are involved in an ice ridge load analysis and the parameters will influence the results depending on the specific site conditions and modeling assumptions. Nevertheless, the order of magnitude of these ice ridge loads prove that ice ridge loads are a primary contributor to the total environmental load on a support structure in Lake Erie.

These extreme ice loads caused by ice ridges can have a significant effect on the total environmental load of a fixed-bottom support structure in eastern Lake Erie, as well as strongly influence the design of the structure. According to Table 2, without the presence of ice, the extreme total environmental loads and moments on a fixed-bottom support structure are similar between a Great Lakes design and an Atlantic Ocean design. In the presence of extreme, or design-driving ice conditions, the total horizontal ice load on a support structure in the Great Lakes more than doubles and the total overturning moment increases by 57%.

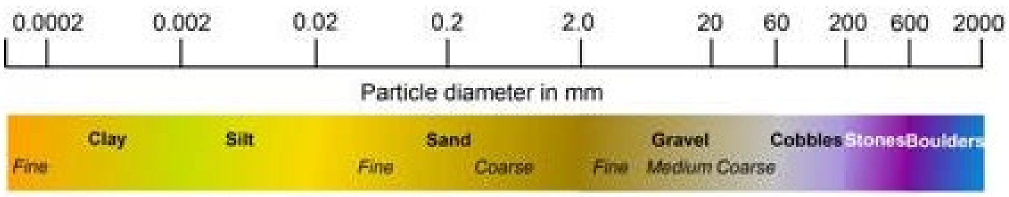
These extreme ice ridge loads are very rare and there is not enough available ice ridge data to be able to accurately quantify the load, but for the purposes of this analysis we estimate a 50-year return period for the extreme ice load. During this extreme event, we assume that hydrodynamic loads are zero because waves and ice floes do not co-exist. In addition, since these conditions are relatively deterministic and predictable, the turbines would also be shut-down to an idling state to minimize aerodynamic loading. Therefore, during conditions when ice ridge loading might occur, the total horizontal load is almost entirely from the ice ridge. As a result of the extreme ice ridge loads, the substructure will likely require modifications that incrementally increase cost. The extent of these impacts is described later in New York State Energy Research and Development Authority (NYSERDA). 2022. “New York State Great Lakes Wind Energy Feasibility Study: Cost Analysis (NYSERDA 2022g).

1.2 Soil Conditions

Another important design driver for fixed-bottom substructures is the lakebed soil conditions. The type, consistency, depth, and strength of lakebed soils can have a large influence on the design of offshore structures. Soil conditions in the Great Lakes are notably different from other parts of the world where offshore structures are developed. Details on the specifics of Great Lakes soils can be found in New York State Energy Research and Development Authority (NYSERDA). 2022. “New York State Great Lakes Wind Energy Feasibility Study: Physical Siting Analysis (NYSERDA 2022b), but the important points are summarized below in relation to how they drive the design of fixed-bottom substructures.

The geophysical characteristics of the Great Lakes are a direct result of glaciation in the region. Figures and data in New York State Great Lakes Wind Energy Feasibility Study: Physical Siting Analysis (NYSERDA 2022b) show that Lake Erie and Lake Ontario consist of soils with a variety of coarseness and strength, ranging from fine clay to large rocks, but primarily consist of a mixture of finer silt and clay. Great Lakes soils can be defined by their particle size, from clay, silt, sand, gravel, and rock soils with lowest to highest particle sizes, in that order, as shown in Figure 4. Some regions near the shore are predominantly made up of sand and rock, but the regions of interest for potential Great Lakes Wind development would be towards the middle of the lakes, which are dominated by clay and silty soils.

Figure 4. Particle Diameter of Common Soils



Another primary design consideration for fixed-bottom substructure design is the bedrock depth below the subsurface, as this can influence the pile driving or cable burial requirements. Again, using figures and data in New York State Great Lakes Wind Energy Feasibility Study: Physical Siting Analysis, (NYSERDA 2022b) the average depth to bedrock in the eastern end of Lake Erie near the middle of the lake is about 30 meters. There are other geohazard considerations that should be considered, such as shallow gas, seismic activity, and soil contamination, but they do not contribute as significantly to the design selection process of fixed-bottom substructures.

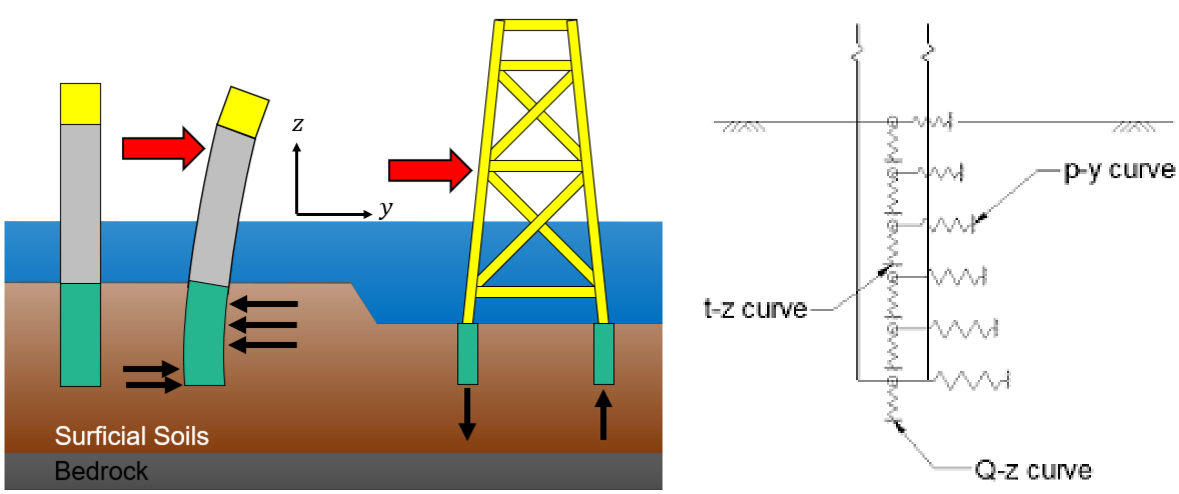
These two soil conditions, soil type and the depth to bedrock, are the primary soil design drivers for fixed-bottom substructure selection. The representative design used in this analysis was not given a specific foundation type, since each potential substructure, while meeting the criterion of having a low profile at the waterline, could have its own distinctive method of attaching to the lakebed. The three most viable fixed bottom foundation types are piles, gravity-base, and suction buckets, but there are new foundation technology variants under development that may be more suitable in response to the different soil and environmental conditions of the Great Lakes.

In general, Great Lakes soils are relatively soft compared to many Atlantic Ocean based sites. According to a geology study conducted by LEEDCo for southern Lake Erie, a soil gradient consisting of shale, till, and postglacial sediment makes up most of Lake Erie. To quantify the strength of this soil, the shear strength of two types of till in the lake was found to range from 0.3-0.7 kg/cm^2 (29.4-68.7 kPa) (Carter et al. 1982). As a comparison, shear strengths of soils in the Sheringham Shoal wind farm in the North Sea range from 20-1,600 kPa depending on the specific location and the depth (Le et al. 2014). These numbers show that in general, Lake Erie soils have lower shear strengths than soils found in other parts of the world, like the North Sea. Exact soil strength data can be available through geotechnical surveys, which will only likely be performed in later studies if Great Lakes Wind development is pursued commercially. However, these shear strengths can be initially used to get a relative sense of the strength of soils in the Great Lakes for a conceptual understanding of the design requirements.

The lower soil strengths may eliminate some fixed-bottom substructure types as viable options for the Great Lakes. Substructures like monopiles are laterally loaded, which means that their deflections are dependent on the strength of the surrounding soils, and the pile geometry (Figure 5a). Monopiles can have an associated "P- y" curve to describe the lateral loads and deflections and are modeled using a series of springs (Figure 5b). Substructures like jackets and tripods have vertically loaded piles on each leg, which means that their deflections are dependent on the vertical external forces, the stiffness of the surrounding soils, and the pile geometry (Figure 5a). These piles can have an associated "Q-z" curve to describe the vertical loads and deflections (Figure 5b).

Figure 5. (a) Lateral and Vertical Loads on a Monopile and a Jacket Substructure; (b) p-y, Q-z, and t-z Curves Used to Describe Soil Stiffness with Multiple Springs

a) b)



The relatively low strength of the soils in eastern Lake Erie will allow larger deflections in laterally loaded support structures that utilize large piles, like monopiles, especially with the added lateral loads from ice ridges. Substructures like tripods that use smaller piles will be affected by the change in soil strength, but not as much as monopiles since these multiple, smaller-diameter pile systems are vertically loaded, and have shown to be effective in soft soils (e.g., Gulf of Mexico). A detailed analyses of substructure response to environmental loading in the Great Lakes is outside the scope of this assessment.

The required penetration depth, or pile fixity length, will vary depending on specific soil strengths, but is commonly estimated to be between 3.5D and 4.5D in stiff clay, where D is the pile diameter (Novák et al. 2017). The length-to-diameter ratio requirement increases as soil strength decreases and can be as high as to 7D–8D for soft silts. For the representative design, assuming the substructure continues into the lakebed with a 6-meter diameter, the penetration depth would be 21–27 meters in stiff clay and can potentially increase up to 42–48 meters in softer soils. The bedrock depth can be close to 30 meters in the central area of eastern Lake Erie, which may allow for pile foundations, but without much margin. If the required penetration depth becomes larger than the depth to bedrock, then pile drilling processes may be an option but would increase the required equipment and cost considerably.

Other foundations, like gravity-base foundations (GBFs), may be challenging in the softer soils of eastern Lake Erie since GBFs require a solid base to rest on to maintain a level orientation and counteract uneven settling of the foundation. Therefore, some degree of surface soil dredging may be required, or alternatively new hybrid GBF foundations may be possible that include other leveling techniques, like a skirted-based or suction buckets, to penetrate below the softer surface layers and provide leveling control of the substructure.

In general, all foundations will require site-specific geotechnical surveys to accurately measure the soil strengths and depth to bedrock, which can determine the overall feasibility of fixed-bottom substructures.

1.3 Local Supply-Chain Limitations

The supply-chain for GLW development will also influence the design selection of a fixed-bottom substructure. Local manufacturing plants and ports may need to be capable of supporting fabrication and assembly of substructures due to the limits in transportation and shipping in the Great Lakes region. The primary Great Lakes supply-chain limitation is the size of the vessel that can navigate through the locks along the St. Lawrence River. A vessel with the ability to install large fixed-bottom substructure components is not likely to be able to navigate the St. Lawrence River, so the conventional methods of installation, as well as other supply-chain processes, will need to be adapted within the region. This limitation is particularly important for Lake Ontario, which has narrow locks connecting to Lake Erie. In Lake Erie, the other Great Lakes (Michigan, Huron, and Superior) may have certain supply-chain advantages that can be utilized. Full details of the supply-chain limitations can be found in New York State Great Lakes Wind Energy Feasibility Study: Infrastructure Assessment (NYSERDA 2022d)

The scale of fixed-bottom wind turbines in Lake Erie will be limited by the capacity of the heavy lift cranes that can be brought in and integrated as part of the infrastructure of the designated marshalling port. The reference turbine for this study is a 6.0 MW turbine based on the conservative assumption that only cranes large enough to lift these turbines would be available. However, the availability of larger cranes with lifting capacities near 600 tons and crane heights over 150 meters would enable the 12 MW to 15 MW turbines that are being procured for offshore wind development in the Atlantic Ocean. These larger turbines would be more visible from shore, but for a given wind plant size, would lower the overall number of structures in the viewshed.

The fixed-bottom substructure design selection will depend on the ability to adapt the port facility for substructure fabrication, quayside turbine assembly, loadout to site, and service. There are three potential ports in eastern Lake Erie capable of supporting fixed-bottom substructure fabrication and installation: Buffalo, Dunkirk, and Erie. The limitations from each of these ports need to be considered in the overall feasibility of a fixed-bottom substructure. However, the substructure design has the potential to adapt to the local supply-chain limitations. Full details of the supply-chain limitations can be found in New York State Great Lakes Wind Energy Feasibility Study: Infrastructure Assessment (NYSERDA 2022d).

2 Fixed-Bottom Substructure Type Feasibility Assessment

Considering the challenges and design drivers in the development of Great Lakes Wind, a feasibility assessment was performed to determine the suitability of fixed-bottom substructures in the Great Lakes. According to the IEC 61400-3-1 standards, a support structure consists of the tower, substructure, and foundation. A substructure is defined as the structural component which extends from the seafloor to connect the foundation to the tower. A foundation is a structural or geotechnical component on or beneath the seafloor to transfer the loads acting on the support structure to the seafloor. The types of substructures being considered in the feasibility study were shown in Figure 1.

The following sections detail general descriptions of each substructure shown in Figure 1 and the advantages and disadvantages they would have in a Great Lakes environment. They are then evaluated for their feasibility in the Great Lakes based on the design challenges and drivers listed in the previous section. Some aspects of each substructure may not be suitable for the Great Lakes, but in many cases, deficiencies may be overcome with reasonable investments. In other cases, substructure deficiencies may be too large to overcome. Note that all of the substructures in Figure 1 meet the general criterion of having slender waterline profiles, except for the jacket, which is not recommended for Great Lakes Wind for this reason. Some of the other substructures are also not likely suitable for the Great Lakes due to other constraints. The optimum substructure candidate for potential Great Lakes Wind development may not be a substructure that currently exists, but an adaptation from one of the following existing types.

2.1 Fixed-Bottom Substructures

2.1.1 Monopiles

Monopiles are the most common fixed-bottom offshore wind turbine substructure. In 2014, out of the 74 wind farms in Europe at the time, 79% had monopile substructures (Sáez 2015). Monopiles are large, hollow steel cylinders that are driven into seabeds and lakebeds to transfer the loads from the wind turbine to the soils and foundation (first from the left in Figure 1). These structures are laterally loaded in bending and are most economical in water depths up to 50 meters if soils are relatively stiff. As with any substructure, their material costs and weight will increase with deeper waters (Wu et al. 2019). The overall length, diameter, thickness, and lakebed penetration depth of a monopile will depend on the specific site conditions, water depth, and environmental loads. However, for a 4–7 MW wind turbine, with a 6 MW turbine being referenced in this study, their lengths are typically 30–70 meters with about 20–30 meters penetrating the lakebed (Energinet.dk 2015). For the larger turbine sizes, their diameters can reach up to 11 meters and their material thicknesses can reach up to 200 mm or more (Schaumann et al. 2014). Monopile substructures typically weigh between 1,000 and 1,500 tonnes or more (Energinet.dk 2015; Schaumann et al. 2014). Monopiles are a well-established, proven technology, which has led to their industrialization in Europe and lower relative costs. They may be more expensive in U.S. markets due to the lack of U.S. steel supplies, manufacturing facilities, and pile driving vessels, but they remain the most common substructure for the near-term offshore wind projects in the Atlantic so far.

Monopiles are affixed to the seabed by pile driving with an impact hammer or vibratory equipment to penetrate the seabed. Piling driving creates loud noises that can be harmful to the surrounding marine life and requires specialized, expensive equipment (Kopp 2010). Monopiles are floated out on either a jack-up vessel, a transport barge, or heavy-lift crane vessel to the site, lifted by crane to its vertical position, and then pile driven or drilled into the lakebed until the desired penetration depth is reached (Kopp 2010; Energinet.dk 2015; Jiang 2021). Depending on the piling conditions and weather conditions, this installation process can take up to 24 hours for one substructure (Energinet.dk 2015). Maintenance processes for monopiles are expensive and the recoverability of pile-driven monopiles is difficult for decommissioning.

Piles in general have a small footprint and low seabed disturbance, so not much lakebed preparation would be required. Monopiles can have a penetration depth of up to 40 meters depending on the environment and are most suited for stiff soils like sand and some clay, and less suited for hard, rocky soils, which would require drilling (Energinet.dk 2015; Keene 2021). The penetration depth can also be a function of the pile diameter: 3.5–4.5 times the pile diameter in stiff clay and 7–8 times the pile diameter in softer soils. They are popular in Europe because of the relative sandy soil conditions of the North Sea. Industry statistics indicate that 60% of monopiles are piled into sand, 14% are piled into clay, and 10% are found in a mixture of sand and clay (Sánchez et al. 2019). Designing adequate scour protection to prevent erosion can help the soil compatibility.

Due to the relatively shallow depth to bedrock, soft soils, the lack of pile-driving vessels in the Great Lakes, and the lack of a local supply chain, traditional monopiles are not recommended for Lake Erie. There are other variants of the conventional monopile that can be considered. LEEDCo had considered a skirted monopile to increase the resistance of the monopile to overcome the lateral loading in the soft soils and shallow bedrock of western Lake Erie. However, only the general monopile is considered for this initial feasibility study, and variants of these substructures will likely be developed further in potential development analyses.

2.1.2 Gravity-Base

Gravity-Base substructures (or gravity base foundations, GBFs) are large, single-column, heavy concrete (or steel) structures filled with high-density ballast to resist the environmental loads using their own gravitational weight (second from the left in Figure 1) (Hammar et al. 2010). They typically have wide, flat bases that rest on the lakebed, providing no tensile forces between the structure and the soil, and taper to a central column where the wind turbine is attached. GBFs are typically used in shallower water depths because they need to be significantly large to resist the environmental loads (Energinet.dk 2015). The base diameters can be adjusted according to the local soil conditions but past applications were on the order of 20–35 meters (Energinet.dk 2015). The central column diameter is typically on the order of 4–6 meters and the overall weight can be upwards of 3,000–4,000 tonnes (Energinet.dk 2015). Like monopiles, GBFs are a well-known and proven technology, and their costs can vary depending on the materials, installation, and water depths (Kopp 2010). In general, they use concrete and steel for construction. Installation methods may vary, but certain GBFs may enable float-out methods to be implemented, which can help mitigate some port and installation logistics barriers. They are low maintenance and longer lasting, but costs and performance have not been demonstrated in deeper waters. Variants of the typical concrete substructures include smaller and tighter steel structures still filled with ballast, as well as regular concrete GBFs with a steel skirt placed around the base to assist in leveling and to reduce dredging in softer soils. GBFs require high lakebed preparation and a significantly high footprint for the removal of low load bearing capacity soils like mud, clay, silt, and sand to make a smooth, hard, and near-horizontal lakebed surface (Wu et al. 2019). They are most suited for rocky bottoms, boulders, and well packed sediments like compacted clay less than 10 meters deep so that time is not wasted dredging for these conditions (Jiang 2021).

The installation process for a typical GBF initially requires 2–5 days to dredge the lakebed to remove any soft soils and create a flat, solid foundation for the substructure to rest. (Energinet.dk 2015; "Review of Options for Offshore Foundation Substructures" 2012). A concrete substructure can be constructed near the port in a dry-dock, or on a floating submergible barge that is transported out to the site by tugboats

(Jiang 2021). Once the lakebed is adequately prepared, the substructure is lowered onto the lakebed by a jack-up vessel or floating crane barge, filled with high-density ballast, usually sand or olivine. After the GBF is set, crushed stone is placed around the base for scour protection. (Hammar et al. 2010). GBFs can be removed if necessary for decommissioning by de-ballasting, or they can be reused.

The extreme ice loads in eastern Lake Erie may require the gravity-base foundations to become larger to counteract the ice loads reacted by the ice cone near the waterline. The equipment needed to lift a heavy substructure like a GBF may not be currently available in the Great Lakes, so custom installation vessels and equipment would either need to be manufactured for the Great Lakes or brought in through the St. Lawrence. GBFs manufactured using concrete would be more cost-effective relative to other steel manufacturing processes in other substructures, but the size and weight would still make the installation difficult. There are potential GBF adaptations that can avoid these vessel and installation limitations by using new float out installation methods and designs to reduce dredging, but more detailed studies are needed to refine these concepts for the Great Lakes.

2.1.3 Jackets

Jacket substructures are tall, lightweight, lattice structures that have multiple interconnecting steel tubular members on three to four legs that anchor into piles in the lakebed (third from the left in Figure 1). ("Review of Options for Offshore Foundation Substructures" 2012; Energinet.dk 2015). The structure is derived from the oil and gas industry for transitional water depths, around 40–50 meters, and provides more support and stability for a wind turbine in deeper waters (Kopp 2010). The piles can be 0.5–2 meters in diameter and are installed similarly to how a monopile is pile driven into the lakebed (Hammar et al. 2010; Sáez 2015). Their weights and dimensions can be tailored to the specific site conditions but in general, jackets are 50–,60 meters in length and weigh 400–600 tonnes, which is relatively low compared to monopiles and GBFs (Energinet.dk 2015; Hammar et al. 2010). Even though the extra cross-members provide great structural rigidity for a higher stiffness and higher load capacity, the cost of materials, construction, installation, and maintenance increases as water depth increases. The piling process for three to four piles in a jacket has less of an environmental impact than monopiles, but still creates some noise and disturbance (Kopp 2010). The use of suction buckets to anchor the legs, rather than piles, is another viable—and less disturbing—solution for lakebed interaction (Jiang 2021).

Overall, due to the complex lattice structure at the water line, which may lead to high ice loads, or ice “jamming,” between multiple legs of the structure, jackets are not suitable for the Great Lakes.

2.1.4 Tripods

Tripods look like monopiles at the waterline, but below the waterline, the center column branches out into three cylindrical steel legs to connect to three medium-sized piles on the lakebed to provide higher rigidity and stability to the wind turbine (second from the right in Figure 1). Tripods can be used in deeper waters, up to 50 meters, to limit the deflections of the single cylindrical monopile and divert the environmental loads to three separate piles (Hammar et al. 2010). The base width, pile penetration, weight, and other dimensions depend on the local site conditions, but they can weigh up to 1,500 tonnes in 40 meters of water depth (Hammar et al. 2010). They are relatively bulkier, heavier, and harder to construct and install, which increases costs. They are not widely used in the fixed-bottom industry.

Figure 6. 5-MW Tripod in Bremerhaven Used in Alpha Ventus under AREVA Multibrid Turbines Taken in 2010 (photo credit Walt Musial)

The tripod is installed by driving three piles into the each of the three legs of the prefabricated substructure. It does not require as heavy, or as specialized, pile driving equipment as a monopile. The use of suction buckets rather than piles is a possible alternative to avoid shallow bedrock (Jiang 2021).

Tripod foundations, like jacket foundations, are most suited for stiff clays and medium-to-dense sands but can be piled in softer soils (Keene 2021). The penetration depth depends on the soil strength (Energinet.dk 2015). Minimal to no lakebed preparation is necessary for the piling process and some scour protection is likely needed. (Hammar et al. 2010). Ice contacting the structure of a tripod is mitigated by outfitting the structure with an ice cone at the water line.

2.1.5 Mono-Buckets

A mono-bucket, or mono-caisson (first from the right in Figure 1), has a single, slender central column, like a monopile, connected to a suction caisson, or suction bucket, attached to the lakebed. Suction buckets are open-ended, upside-down, steel buckets that use vacuum pressure to penetrate into the lakebed without the need for pile driving, they have low noise during construction, require little preparation of the lakebed, and have relatively low environmental impacts. The larger, steel cylindrical suction bucket is mounted to the smaller, steel cylindrical shaft and driven into the lakebed using vacuum pressure (Fernández 2010). Mono-buckets are likely to be feasible in a range of water depths from 15 to 55 meters (Sáez 2015), which corresponds to the depth range under consideration for Lake Erie. Mono-buckets are expected to be highly durable, require no specialized installation vessels, and have higher vertical and lateral load capacity.

In one example from Germany, the diameter of the mono-bucket for an 8.4 MW wind turbine was about 19 meters ("Deutsche Bucht Will Install Two Turbines on Mono Buckets" 2018); however, the project was not completed due to problems encountered during installation. The Icebreaker project off Lake Erie proposes the use of mono-buckets for 3 MW wind turbines, with a bucket diameter of 17 meters, a height of 6.75 meters, and a weight of 374 tons.

A mono-bucket substructure can be towed to its site by small vessels or floated out on a barge, upended by either a crane on a jack-up vessel or ballast, and then allowed to sink into the soil and produce suction until the target soil penetration depth is reached (Kopp 2010). The installation is expected to be relatively fast, quiet, and can be reversed and recovered for decommissioning (Energinet.dk 2015). Variants of mono-buckets have been proposed that can include concrete buckets with steel skirts to enable soil penetration and to improve load carrying capacity (Fernández 2010).

Mono-buckets are particularly attractive in areas where bedrock is close to the surface and deep piles are not possible. They are most suitable in soft and homogeneous soils, like sand, silts, and clays, without hard layers or rocks (Energinet.dk 2015). The required penetration depth is low compared to piles (Kopp 2010). Since a mono-bucket has a similar waterline profile as a monopile, it will have similar ice load reactions and can be outfitted with an ice cone to deflect ice floes. The primary drawback of mono-buckets is that the industry has very limited experience with them. Therefore, there is a high degree of uncertainty with cost and performance, and the available data is limited.

According to LEEDCo, mono-buckets were determined to be one of the most feasible options in western Lake Erie near Cleveland due to the soft soils and the shallow bedrock but could also be feasible in eastern Lake Erie, as the soil conditions are similar.

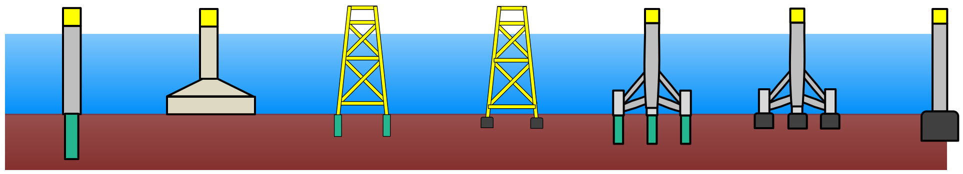
2.2 Substructure Feasibility

Each fixed-bottom substructure type and some additional variants were evaluated on six different criteria and rated according to their feasibility in the Great Lakes, specifically, Lake Erie.

1. **Installation Ability** is assessed based on the support structure's potential to be compatible with local port facilities to enable the use of float-out installation methods or available lake vessels for installation, commissioning, and service.
2. **Lakebed Compatibility** is assessed based on how suited the substructure's foundation is for the soil conditions of eastern Lake Erie.
3. **Ice-structure Interaction** is based on the substructure's ability to achieve a slender waterline profile.
4. **Local Manufacturability** is based on the potential to adapt the substructure for manufacturing in the Great Lakes region, including the Northeast U.S. and the Midwest.
5. **System Cost** is evaluated based on the substructure's ability to minimize the cost of all parts of the design process considering the primary design challenges and constraints of Lake Erie.
6. **Technology Readiness** is an assessment of the risk associated with a support structure's maturity within the global industry and degree to which it can be fully commercialized.

Table 3 shows the ratings for each substructure for each criterion in a value of "red," "yellow," or "green." A "red" box indicates that a substructure has a major limiting factor for that criterion and may be unsuitable. A "yellow" box indicates that a substructure could be feasible for that criterion, but it may be difficult, or not ideal, to implement. A "green" box indicates that a substructure fits that criterion well.

Table 3. Feasibility Assessment of Fixed-Bottom Substructure Types

Fixed-Bottom Criterion	Monopile	Gravity-Base	Jacket (piles)	Jacket (suction buckets)	Tripod (piles)	Tripod (suction buckets)	Mono-Bucket
							
Installation Ability	Red	Yellow	Yellow	Green	Yellow	Green	Green
Lakebed Compatibility	Red	Yellow	Yellow	Green	Yellow	Green	Green
Ice-Structure Interaction	Green	Green	Red	Red	Green	Green	Green
Local Manufacturability	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
System Cost	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Technology Readiness	Green	Green	Green	Yellow	Yellow	Yellow	Yellow

From this qualitative assessment, the substructures with a major limiting factor are monopiles and jackets. Monopile foundations are likely not to be feasible in eastern Lake Erie due to the lack of soil strength, the potential of contacting bedrock, and the lack of pile driving vessels available in the Great Lakes. While the soil depths are marginally sufficient for smaller multi-pile substructures such as jackets, and with the assumption that it can be reasonable to access standard pile driving equipment on the Great Lakes, jackets are not considered to be feasible in the Great Lakes due to their incompatibility with ice and the structural uncertainty of predicting ice loading.

Gravity-base foundations, tripods with piles or suction buckets, and mono-buckets did not have any major limiting factors (red) restricting their deployment in eastern Lake Erie. All four types have slender waterline profiles, which can be outfitted with ice cones to reduce ice loads on the structure. Gravity-base foundations may require significant lakebed preparation (or design modification) and dredging depending on the site-specific conditions, but they have potential for design modifications to minimize these issues. The addition of an annular skirt around bottom circumference could help level the substructure and avoid much of the lakebed preparation and dredging that would probably be required to reach level, firm soils. Suction buckets are suitable for the soils of eastern Lake Erie and may offer easier installation procedures than other foundations, but they have not yet been demonstrated on a commercial scale.

The manufacturability and cost of any substructure deployed on the Great Lakes will be challenged by supply-chain development because there are no facilities currently available. The optimal fixed-bottom substructure type for Great Lakes Wind will likely be some adaptation of one of the substructures that meets the ice, geotechnical, and logistical requirements for Lake Erie, introducing advancements necessary to account for the lake's unique physical and logistical conditions.

3 Ice Floe Modeling for Fixed-Bottom Systems

The presence of ice in Great Lakes waters poses a new and significant design consideration for Great Lakes Wind. To properly design wind turbine substructures for the Great Lakes, the modeling and simulation tools need to be able to incorporate structural ice loads and their effect on the system design.

Multiple ice loading methods and models have been developed for use in designing offshore structures, including offshore wind turbines, over the past decade. An ice loading method is a systematic approach to calculate the forces that ice exerts on an offshore structure. An ice loading model is an implementation of a specific ice loading method to determine the ice forces and other effects. An ice module is the computer code or software that contains various ice models to enable ice loading to be incorporated as part of a larger simulation.

The two most common and most notable ice load methods are the Ralston method and the Croasdale method. Both methods are used to calculate the ice loads on a sloped structure and are referenced in the ISO 19906 standards (International Organization for Standardization 2010). Each one uses various techniques that consider the different forces that arise on a sloped structure when an ice sheet breaks, rides-up the slope, and creates ice rubble. Both methods predict reasonable loads on a structure and a preference between the two is dependent on the specific ice-structure scenario. However, these methods should not be used to calculate the ice load on a structure if the ice fails in a mode other than bending. Other methods, such as ice crushing, can be referenced in the following ice modeling sections, but are not considered in this study.

One of the most widely used modeling tools used for designing offshore (fixed-bottom or floating) wind turbines is OpenFAST, which NREL developed to simulate the coupled dynamics of offshore wind turbine systems. OpenFAST contains two ice modules, IceDyn and IceFloe. IceDyn was developed in 2015 by Dale Karr at the University of Michigan (Karr, Yu, and Sirnivas 2015) and IceFloe was developed in 2016 by Tim McCoy at DNV (McCoy 2014). Both modules include a set of ice models that reference various standards and methods to simulate the ice loads on an offshore structure in different failure modes. For example, the module IceDyn has an ice bending model for sloping structures that uses the Ralston method to calculate ice loads on the structure. Because Great Lakes Wind substructures will most likely be outfitted with sloped ice cones, the ice bending models in IceDyn and IceFloe will be of primary interest. The other models in IceDyn and IceFloe are useful for simulating other ice-structure interactions scenarios but will not be as relevant to this feasibility study.

The following describes the state of the art in predicting ice loads on offshore structures, with an emphasis on the two open-source ice modules that are part of OpenFAST, IceDyn and IceFloe. Other ice modeling tools in industry, mostly proprietary, have been used for ship and similar offshore structure applications, which are also discussed. Note that most of the modeling tools discussed herein were developed for fixed-bottom substructures. Ice models for floating wind substructures are in earlier stages of development, but the fixed-bottom tools may provide a reasonable first order approximation.

3.1 IceDyn

IceDyn is the first of two ice modeling tools that were developed for the OpenFAST simulation framework. The IceDyn module was developed by Dale Karr and Bingbin Yu at the University of Michigan to include static and dynamic ice loading during a dynamic simulation of an offshore wind turbine. The IceDyn module considers ice failure modes of spalling, buckling, crushing, splitting, and bending in its models and sub-models and determines the subsequent effects on the structure. OpenFAST has the capability of running with or without this module, as well as being able to run this module with or without any other module. The number of legs of the substructure can be specified, each with their own position and diameter. There is not one specific sub-model in IceDyn that is used to cover all ice scenarios. Because ice behaves in different ways depending on the scenario, IceDyn contains six models with a different number of sub-models within each model for a total of 12 ice scenarios, all of which are outlined in Table 4. The desired model and sub-model must be specified in the IceDyn input file, as well as many sub-model-specific ice characteristic inputs, for any given simulation. Table 4 lists the models and sub-models, the typical ice load time series, and the maximum ice load for that typical time series for a set of extreme ice-structure properties characteristic of Lake Erie. "Typical" time series are used to show the general shape of an ice load time series for the given set of IceDyn inputs. Varying the ice properties and settings can change the trend of the time series, but for extreme Lake Erie ice properties and default settings, IceDyn produces the following ice load time series for each sub-model.

Table 4. IceDyn Sub-model Descriptions, Ice Load Time Series, and Maximum Loads

Source: "Karr, Yu, and Sirnivas 2015"

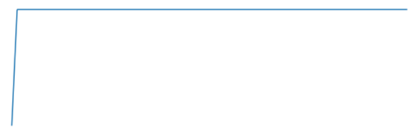
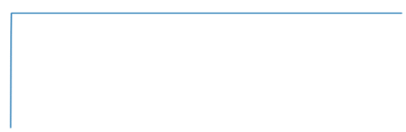
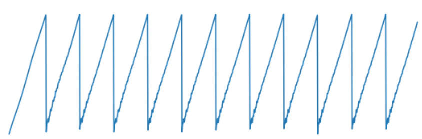
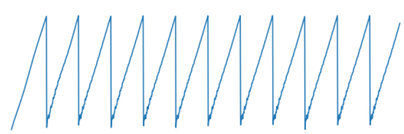
No.	Model	Sub-model	Ice Load Typical Time Series	Maximum Ice Load in Typical Simulation (MN)
1-1	Quasi-Static Ice Crushing Model	Creep	 Ice is modeled as a creep material floating around a rigid structure and continuously exerts a force on the structure.	10
1-2		Elastic Buckling	 Ice is modeled as a wedge-shaped plate of elastic material on an elastic foundation (water surface) and exerts a large initial force which then quickly breaks apart.	10
1-3		Prescribed Creep	 The continuous force that the ice exerts on the structure is based on a normal failure stress prescribed by the user.	5
2-1	Dynamic Ice/Structure Interaction Model	Single tooth deflection	 Ice "teeth" deflect one at a time when ice contacts the structure, causing the tooth to fail in a ductile or brittle mode and exert repeated forces on the structure.	10
2-2		Two ice teeth deflection	 Multiple ice "teeth" can deflect at the same time when ice contacts the structure, causing the teeth to fail in a ductile or brittle mode and exert repeated forces on the structure.	10

Table 4 continued

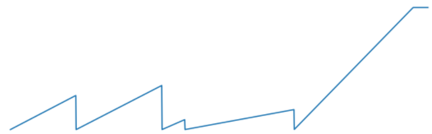
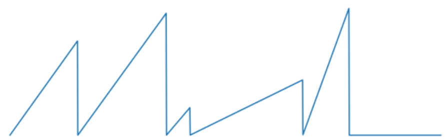
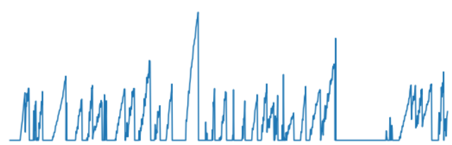
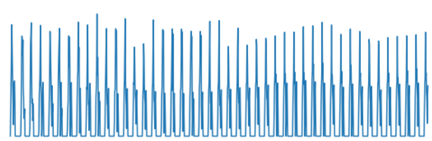
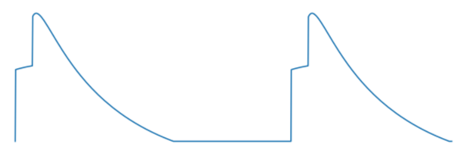
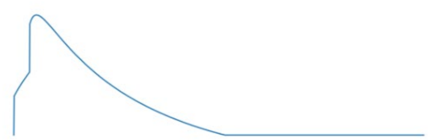
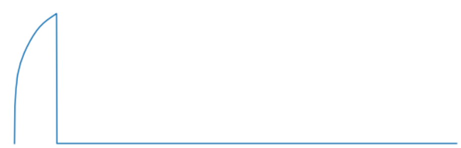
No.	Model	Sub-model	Ice Load Typical Time Series	Maximum Ice Load in Typical Simulation (MN)
3-1		Creep	 Ice velocity and thickness are considered random variables, using low indentation speeds to model creep.	10
3-2	Random Vibration Model	Continuous Crushing – static	 Ice brittle strength is the random variable, while other ice characteristics are deterministic, to produce a continuous crushing load on the structure.	10
3-3		Continuous Crushing – dynamic	 Ice brittle strength and ice teeth properties from model 2 are treated as random variables to apply the theory from model 2 to a continuous crushing model.	20
4	Multiple Failure Zone Model	-	 Calculates the ice load changes due to non-simultaneous ice failure in local ice-structure contact zones.	5

Table 4 continued

No.	Model	Sub-model	Ice Load Typical Time Series	Maximum Ice Load in Typical Simulation (MN)
5-1	Ice Bending Model for Sloping Structures	Ralston	 The ice load assumes ice rubble ride up on a conical structure and exerts a lower force due to bending.	0.5
5-2	Ice Bending Model for Sloping Structures	Augusti/Yu	 The ice sheet is modeled as a rigid-plastic structure on an elastic foundation contacting a conical structure.	0.5
6	Ice Floe Impact Model	-	 Ice is modeled as a large ice floe that collides head-on with the structure, decelerating the ice floe until the floe stops, bounces back, or breaks into multiple pieces.	8

3.1.1 Capabilities

Out of the six models in this module, only one is of primary concern when predicting ice loads on potential Great Lakes Wind substructures. The fifth model is the ice bending model, which assumes an ice cone, or slope, at the substructure's waterline. Substructures in the Great Lakes will likely be outfitted with ice cones to reduce the ice loads on the structure, since the ice bending mode of failure generally exerts the lowest load on a structure. This model is the most representative of typical ice-structure interactions in the Great Lakes and will be the design-driving ice-structure scenario. When an ice sheet contacts a sloped structure, it fails in bending by riding up (or down) the slope and then pushes the broken ice pieces farther up (or down) the slope. There are many analytical methods associated with this mode of failure to calculate the forces from the ice sheet on the slope. IceDyn references the Ralston method (Ralston 1980), which is a well-known ice bending load method, and the Augusti/Yu method (Karr, Yu, and Sirnivas 2015), which models the ice as a rigid-plastic structure against an elastic foundation.

The remaining IceDyn models that do not simulate ice failing in the bending mode are of less interest to Great Lakes Wind ice load prediction, but still relevant to report IceDyn's capabilities. The first model is a quasi-static ice crushing model, which assumes a rigid support structure with negligible displacement of the structure relative to the ice. In this scenario, ice can fail in multiple crushing modes depending on the given ice characteristics, such as ice velocity or ice thickness. Therefore, there are multiple sub-models to ensure that the correct mode of failure is simulated.

The second model is a dynamic ice/structure interaction model that considers the offshore structure as a compliant structure and can displace in response to the ice force. Ice fails in the ductile or brittle modes depending on the indentation speed (Karr, Yu, and Sirnivas 2015). This model utilizes a method to represent the ice sheet as a series of brittle elastic teeth, similar to a comb, where the teeth move past a mass (the structure) at a given speed and increase the load on the structure until the teeth (ice) break and the load goes to zero. That process is repeated for the specified amount of simulation time. There are two sub-models to include the randomness in how different sections of an ice sheet start to fail when in contact with a structure.

The third model is a random vibration model to consider the probabilistic nature of ice failing, rather than a deterministic nature. The ISO 19906 standards explain how different ice properties (thickness, velocity, stress, temperature, etc.) vary randomly in time and space and how the ice load on a structure can have a random pattern resulting in random vibrations (International Organization for Standardization 2010). The first sub-model considers random ice properties with a low indentation speed to model the creep mode of failure. The second and third sub-models consider random ice properties as well but with higher indentation speeds to fail in a more brittle mode, otherwise known as continuous crushing. This is done for a static non-compliant structure, as well as a dynamic, compliant structure, respectively.

The fourth model is a multiple failure zone model which considers the mode of non-simultaneous localized failure of the ice sheet across the entire contact area with the structure, especially at higher indentation speeds. A common analogy is a piano with varying key lengths being pressed up against a wall; the longer piano keys will break before the shorter ones, modeling the non-simultaneous local failure of an ice sheet. This is why the typical time series for this model is more active, since it's calculating the force required to break small sections of the same ice sheet.

The sixth and final model is the ice floe impact model. Rather than assuming the ice constantly moves in one direction against the structure, this model considers the dynamics of a large ice floe. It models an ice floe contacting a structure, increasing its applied force over time, but also losing velocity at the same time until the velocity goes to zero and the ice floe stops, bounces backwards, or splits and floats around the structure. However, if an external environmental force is strong enough to keep the ice floe in contact with the structure, it can cause continuous crushing.

3.1.2 Limitations

Even though IceDyn can consider 12 different types of ice failure scenarios, there are some aspects that are not included. There is no specific capability to model ice ridge loads. Ice ridges are likely to be the design driver in ice load calculations and IceDyn does not seem to consider these phenomena. Secondly, IceDyn cannot be simulated at the same time as HydroDyn, which is the OpenFAST module that calculates the hydrodynamic loads on the structure, since the module only considers extensive ice cover and the interaction of large ice floes with an offshore structure. In most ice-structure scenarios, waves do not exist when there is extensive ice cover. However, there can be scenarios with less extensive ice cover where some waves and currents can potentially affect the structure's natural frequencies, hydrostatics, and the response, which the OpenFAST would not capture. Lastly, compared to other OpenFAST modules, there seems to be limited documentation on the module other than the primary IceDyn reference.

3.1.3 Validation Efforts

Validation of the IceDyn module is limited due to the lack of experimental data available at the time IceDyn was written, and such a validation program would be expensive. VTT Technical Research Center of Finland (VTT) may have experimental data on monopiles and lighthouses in icy waters that can be used for validation, but none were available for IceDyn validation purposes. The analytical results from IceDyn were compared to ice loading theory and were verified for a standard monopile and jacket foundation. There are no other known validation efforts.

3.2 IceFloe

IceFloe is the second of the two ice modeling tools that are incorporated into the FAST framework to simulate ice effects on an offshore wind turbine. The IceFloe module was developed by Tim McCoy at DNV at a similar time as IceDyn but with a larger focus on meeting the design requirements of ice on offshore wind turbines as specified in IEC and ISO offshore wind turbine design standards. Similar to

IceDyn, OpenFAST has the capability to run with or without IceFloe, as well as being able to run IceFloe with or without any other OpenFAST module. Like IceDyn, the number of legs of the structure can be specified with their own positions and diameters, except it only allows inputs of one, three, or four legs. There is not one specific method in IceFloe that is used to cover all ice scenarios. IceFloe is split up into seven models with no sub-models. The model type is specified in the IceFloe input file, along with the necessary inputs (McCoy 2014). Table 5 lists the models, the typical ice load time series, and the maximum ice load for that typical time series for a set of extreme ice-structure properties characteristic of Lake Erie. "Typical" time series are used to show the general shape of an ice load time series for the given set of IceFloe inputs. Varying the ice properties and settings can change the trend of the time series, but for extreme Lake Erie ice properties and default settings, IceFloe produces the following ice load time series for each model.

Table 5. IceFloe Model Descriptions, Ice Load Time Series, and Maximum Loads

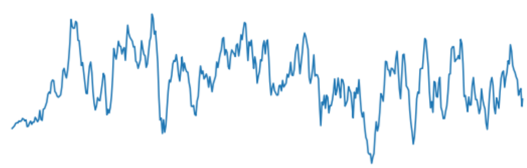
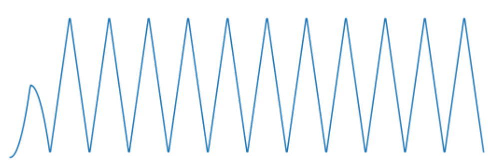
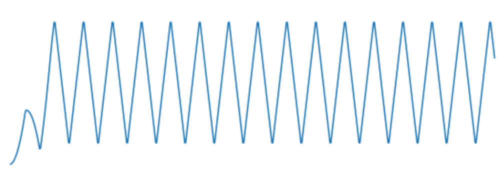
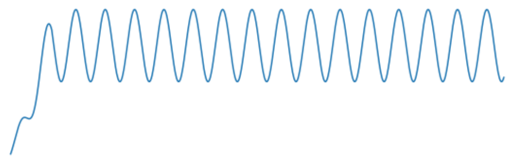
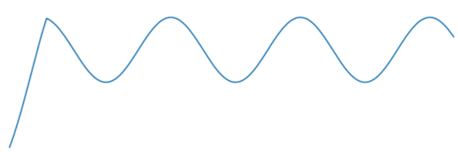
No.	Model	Ice Load Typical Time Series	Maximum Ice Load in Typical Simulation (MN)
1	Continuous Random Crushing	 The ice sheet velocity is used as a random variable in calculating the ice force while failing in a continuous crushing mode.	5
2	Intermittent Crushing per ISO	 Ice sheet velocity is set as an intermediate velocity, which produces dynamic ice loads determined by the level of brittle crushing.	5
3	Lock-in Crushing per ISO	 A unique case of intermittent crushing where the ice load frequency is the same as the natural frequency of the structure, using triangular waveforms as specified by ISO.	5

Table 5 continued

No.	Model	Ice Load Typical Time Series	Maximum Ice Load in Typical Simulation (MN)
4	Lock-in Crushing per IEC	 A unique case of intermittent crushing where the ice load frequency is the same as the natural frequency of the structure, using sinusoidal waveforms as specified by IEC.	5
5	Coupled Crushing	 The instantaneous ice load, due to ice failure in crushing, depends on the relative velocity between the ice and structure.	10
6	Flexural Failure per ISO	 The ice sheet is assumed to ride up a conical structure and fail in its bending mode, producing triangular load waveforms, per ISO.	0.5
7	Flexural Failure per IEC	 The ice sheet is assumed to ride up a conical structure and fail in its bending mode, producing sinusoidal load waveforms, per IEC	0.5

3.2.1 Capabilities

Out of the seven models in this module, similar to IceDyn, only the models that simulate ice failing in bending is of primary concern when predicting ice loads on potential Great Lakes Wind substructures. The sixth and seventh IceFloe models consider the flexural bending mode of failure for ISO standards and IEC standards, respectively. The ISO standard model utilizes the Croasdale method for flexural bending loads and represents the loads as a sawtooth waveform with random periods and peak heights. The IEC standard model utilizes the Ralston method for flexural bending loads and represents the loads as a sinusoidal waveform at a frequency well-below the structure natural frequency. Substructures in the Great Lakes will likely be outfitted with ice cones to reduce the ice loads on the structure, since the ice bending mode of failure generally exerts the lowest load on a structure. These IceFloe models are the most representative of typical ice-structure interactions in the Great Lakes and will be the design-driving ice-structure scenarios.

The remaining IceFloe models that do not simulate ice failing in the bending mode are of less interest to Great Lakes Wind ice load prediction, but still relevant to report IceFloe's capabilities. The first model in IceFloe is a continuous random crushing model which models an ice sheet moving at a high velocity against a structure and failing in the crushing mode in a random pattern. The second model is an intermittent crushing model which has lower, intermediate ice velocities but still fails in the crushing mode. It has a prescribed sawtooth waveform and accounts for the dynamics between the ice and the structure since the downslope of the sawtooth function is determined by the structure's damping properties. The third and fourth models consider scenarios when the ice indentation frequency matches the structure's natural frequency, something which IceDyn does not consider. This form of intermittent crushing can cause the structure to have a large dynamic response and "lock-in" to the frequency of the system. This is modeled in the third model using standards from ISO with a sawtooth waveform and in the fourth model using standards from IEC with a sinusoidal waveform. The fifth model is a coupled crushing model that is similar to the lock-in model, but the instantaneous load is dependent on the relative velocity between the ice and the structure, so it includes more of the dynamics of the ice-structure interaction.

3.2.2 Limitations

IceFloe has similar limitations as IceDyn. There is no consideration for ice ridge loading in IceFloe. There are sections of the ISO standards that mention ice ridges, but the theory does not translate to any model in IceFloe. Like IceDyn, IceFloe cannot be simulated at the same time as HydroDyn, which calculates the hydrodynamic loads on the structure. In most ice-structure scenarios, waves do not exist when there is extensive cover. However, there can be scenarios with less extensive ice cover where some waves and currents can affect the simulation. IceFloe only has seven models compared to IceDyn's 12, and those seven models are only variations of two types of ice failure: crushing and bending.

3.2.3 Validation

According to DNV, experimental ice loading validation data was not available because it is held confidential by commercial and academic institutions (McCoy 2014). Therefore, the validation of the module was limited to check for reasonable results and compare to available ice data on bridges and other cold-environment structures. The two steps of verification that were performed were first, a check of the outputs manually to ensure the program was running correctly, and secondly, to run the module over a wide range of inputs and to analyze the results for any outliers. These verification tests were run and helped gain some confidence in the accuracy of the models, but the validation was not carried out on experimental data, since it was not available. The module was also simulated through multiple load conditions in FAST, as well as other simulation tools such as HAWC2, Bladed, and ADAMS to ensure the couple processes fit within the larger simulation.

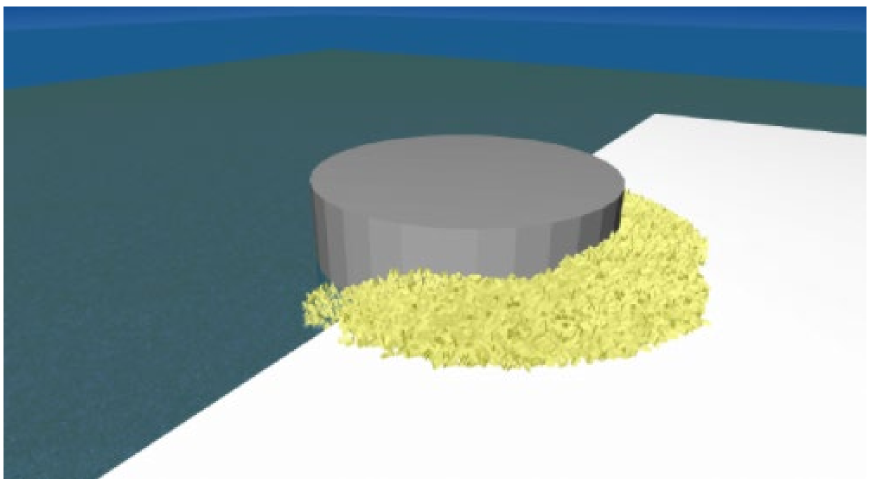
3.3 Other Ice Models

There is a wide range of other ice modeling tools in industry, some focusing on the ice-structure interaction with offshore structures and some focusing on the ice-structure interaction with ships. Research and experimental tests are being performed on these topics in multiple European locations, such as Frauenhofer IWES, VTT Technical Research Center of Finland, and the Hamburg Ship Model Basin, but the experimental model test data collected by these types of institutions is not publicly available, making validation efforts difficult. IceDyn and IceFloe are tools that can model ice interactions with offshore wind turbine structures and have the benefit of being open source. The following is a survey of other ice-structure models in the industry, most of which are not open source.

Bureau Veritas (BV) is an international classification society that worked with other institutions to develop IceSTAR (Cambos 2014), a software program to analyze hull structure strength for ships traveling through ice. DECICE is a discrete element numerical modeling program, developed by INTERA Technologies, to calculate ice loads on a ship and other ice-ship interaction scenarios, such as maneuverability processes (Zhan et al. 2010). SBM Offshore has developed ADWICE, an engineering tool to calculate ice loads on a weathervaning ship with a turret-mooring system for Arctic production (Hidding, Bonnaffoux, and Naciri 2011). ADWICE uses an ice method referenced in ISO 19906 (International Organization for Standardization 2010), which is also used in IceFloe. Model tests of the turret used in ADWICE have been performed and validation tests were run, showing a reasonable agreement in numbers. SimShipIce is a numerical model that simulates moored structures in response to variable ice drifting actions, including ice ridges (Bonnemaire et al. 2014).

Ice-MAS is an ice simulation tool that predicts the ice-structure flow interaction for fixed and floating structures to calculate the ice loads (Septseault et al. 2015). It is developed by TechnipFMC, Cervval, and BV, which are all companies in France. It can simulate the effect of ice rubble pile-up and ice ridges on multiple legs of a structure and return the ice loadings on each leg, whether it has a vertical or sloped profile (Figure 7). It was originally written for projects in the North Caspian Sea but can be applied to all arctic-related scenarios. The results from Ice-MAS are reasonable and are validated against published data (Septseault et al. 2015).

Figure 7. Example Ice-MAS Ice-Structure Interaction with Rubble in Crushing



Another aero-hydro-servo-elastic simulation tool, OneWind, which is developed at Frauenhofer IWES, couples a soil-structure-ice interaction model (PSSII) for vertical structures, and an ice load bending failure model for sloped structures to its simulations (Jussila, Popko, and Heinonen 2013). The simulations were compared to ABAQUS simulations, and the responses show good agreement with the experimental data.

SHIVER is a project run by Delft University of Technology, Aalto University, and Siemens Gamesa Renewable Energy to develop an advanced ice model for design and optimizing offshore wind turbines ("SHIVER – An Advanced Ice Model for Designing Offshore Wind Turbines" 2019). A model-scale offshore wind turbine will be used for laboratory ice model tests at Aalto University. It will have an emphasis on determining the details of the physical ice-structure interaction, as well as the effects of ice-induced vibrations.

Lastly, the Icebreaker project led by LEEDCo has the goal of constructing and installing six 3.45 MW offshore wind turbines in Lake Erie, 8 miles north of Cleveland, Ohio. During their planning of ice load methods, they referenced the methods detailed in ISO 19906 and then reassessed the ice load calculation procedures based on Confederation Bridge data (Allyn and Croasdale 2016). These revised calculations were completed in a spreadsheet-style format to produce horizontal ice loads on an offshore wind turbine in Lake Erie conditions. Even though this is not a specific software tool or model, it is still a noteworthy method to mention to accurately calculate ice loads on offshore wind turbines, especially in the Great Lakes.

3.3.1 Ice Ridge Methods

The previously mentioned models mostly assume that the style of ice interacting with an offshore structure is thin, level ice. However, there is some evidence of ice ridging in the Great Lakes, where the individual ice sheets collide and slide under, slide over, or break against other ice sheets, resulting in an accumulation of ice broken ice rubble that can form a deep ridge. Ice ridges need to be accounted for in modeling ice loads on offshore structures because they are likely to produce the highest ice load on a structure.

As with most ice load methods and models, ice ridge loads are highly variable and difficult to accurately predict. To analytically solve for these loads, the force from the consolidated layer of the ice ridge can be calculated using any existing method or model whereas the force from the ice ridge keel should be calculated separately. ISO 19906 provides guidance on the recommended method to calculate the force from an ice ridge keel and lists the references for ice ridge load determination. The standard states that the load can be assumed to contact a structure at one-third of the keel depth below the base of the consolidated layer.

The Icebreaker project led by LEEDCo provides their own process in determining ice ridge loads on vertical and sloped structures, while referencing ISO 19906 and developing their own estimation methods (Allyn and Croasdale 2016). Their method expands on the ISO 19906 standards and includes frictional and cohesion shearing considerations, the trapezoidal shape assumption of the ridge, and a shear plug model in an attempt to better predict the loads on vertical and sloped structures. After their analysis, they derived a design load of 7.4 MN from an ice ridge with a consolidated layer thickness of 1.1 meters and a keep depth of 16 meters in Lake Erie. 7.4 MN is almost an order of magnitude above the rated wind thrust force for the NREL 5 MW wind turbine, although it is applied much lower on the support structure. These numbers are fairly reasonable for other parts of Lake Erie, such as eastern Lake Erie, since all areas of the lake will have similar environmental conditions.

3.4 Gaps Assessment with IEC 61400-3-1

The design requirements from IEC 61400-3-1 state that ice needs to be considered in the same way that other environmental conditions are considered, such as wind or waves, in the design of an offshore wind turbine. Ice can either produce static loads from fast ice cover, or dynamic loads from wind and current induced motion of the ice floes. The offshore structure design needs to include the ice thickness with a 50-year recurrence period, the ice crushing strength, the risk of current or wind induced ice floes, the risk of forces induced by a changing water level, and the frequency of ice concentration (International Electrotechnical Commission 2009). In addition to the standard offshore wind turbine design load cases (DLCs), the IEC standard includes DLCs with ice. Table 6 is a snapshot of the ice DLC table in the IEC standards.

Table 6. Design Load Cases for Ice

Source: "International Electrotechnical Commission 2009"

Design situation	DLC	Ice condition	Wind condition	Water level	Type of analysis	Partial safety factor
Power production	E1	Horizontal load from temperature fluctuations	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out} Wind speed resulting in maximum thrust	NWLR	U	N
	E2	Horizontal load from water fluctuations or arch effect	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out} Wind speed resulting in maximum thrust	NWLR	U	N
	E3 For extrapol-ation of extreme events	Horizontal load from moving ice floe at relevant velocities $H = H_{50}$ in open sea $H = H_m$ for land-locked waters	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out} Wind speed resulting in maximum thrust	NWLR	U	N
	E4	Horizontal load from moving ice floe at relevant velocities $H = H_{50}$ in open sea $H = H_m$ for land-locked waters	$V_{in} < V_{hub} < V_{out}$	NWLR	F	*
	E5	Vertical force from fast ice covers due to water level fluctuations	No wind load applied	NWLR	U	N
Parked	E6	Pressure from hummocked ice and ice ridges	EWM Turbulent wind model $V_{hub} = V_1$	NWLR	U	N
	E7	Horizontal load from moving ice floe at relevant velocities $H = H_{50}$ in open sea $H = H_m$ for land-locked waters	NTM $V_{hub} < 0.7\ V_{ref}$	NWLR	F	*

DLC	design load case
EWM	extreme wind speed model (see IEC 61400-1)
NTM	normal turbulence model (see IEC 61400-1)
NWLR	normal water level range (see 6.4.3.1)
F	fatigue (see 7.6.3)
U	ultimate strength (see 7.6.2)
N	normal
*	partial safety factor for fatigue (see 7.6.3)

The first five DLCs are in the power production design scenario, where the turbine is operating normally, and the last two DLCs are in the parked design scenario, where the turbine is not operating but is still being affected by the environment. DLC E1 contains a horizontal load from fast ice cover originating from temperature fluctuations. DLC E2 contains a horizontal load from fast ice cover originating from water-level fluctuations and arch effect. DLCs E3, E4, and E7 all contain horizontal ice loads that should be estimated using a crushing method for vertical cylindrical waterline profiles and a standard bending method for sloping waterline profiles. DLC E5 contains vertical loads from fast ice cover using a vertical load shear strength method. Lastly, DLC E6 covers the extreme conditions of ice and wind loads and includes the large loads that result from ice ridges interacting with a structure. The standards state that "It is generally not recommended to install wind turbines in area with the risk of ice ridging." Table 7 shows a gaps assessment between the two ice modules, IceDyn and IceFloe, and whether they have the capabilities to simulate these DLCs as outlined by the IEC standards. Other ice modeling tools are not considered in this gaps assessment because there is not enough available data to determine if they are capable of simulating each of these DLCs.

Table 7. Gaps Assessment of IceDyn, IceFloe and the IEC 61400-3-1 Standards (International Electrotechnical Commission 2009)

DLC	Situation	DLC Description	IceDyn Capability	IceFloe Capability
E1	Powered	Horizontal load from temperature fluctuations	-	-
E2	Powered	Horizontal load from water-level fluctuations and arch effect.	-	-
E3	Powered	Horizontal load from crushing method on vertical shapes and bending method on sloped shapes.	X	X
E4	Powered	Horizontal load from crushing method on vertical shapes and bending method on sloped shapes.	X	X
E5	Powered	Vertical load from ice frozen to structure during fluctuating water levels.	-	-
E6	Parked	Load from ice ridges.	-	-
E7	Parked	Horizontal load from crushing method on vertical shapes and bending method on sloped shapes.	X	X

IceDyn and IceFloe have many different methods to calculate the ice loads on an offshore wind turbine structure to include various ice failure modes. However, they do not include all aspects of ice loads as outlined by the IEC 61400-3-1 standard requirements. None of the sub-models in the two modules include considerations for loads resulting from temperature fluctuations, water-level fluctuations, or ice ridges. Ice ridges are likely to be design drivers for some cold-environment offshore wind structures in Lake Erie, which the two ice models do not include.

In contrast, the ISO 19906 standard includes design considerations and calculations for most of these requirements, such as temperature loads and ice ridge loads. The ISO standards do not provide specific requirements in the form of DLCs that the IEC standards do, but the ISO standards have more ice action considerations that can be applied to more models and methods. However, the IEC 61400-3-1 standards provide extra requirements in terms of stochastic simulations and model testing. They recommend basing response simulations and producing time series of ice loads primarily on ice model tests. For model testing, the standards recommend testing with artificial ice and using Froude scaling to accurately model the resonance frequency, damping, and stiffness of the structure.

3.5 Summary

For any offshore wind turbine development in cold-weather environments, modeling and simulation tools need to be able to account for ice loads on a design. There are multiple ice load calculation methods and tools in industry to simulate the effects of ice, most of which are proprietary but two of which are open-source and are integrated into the OpenFAST simulation tool, IceDyn and IceFloe. These tools were mostly developed for fixed-bottom offshore structure applications. IceDyn contains six ice models and 12 ice sub-models and IceFloe contains seven models that each reference various standards and methods to calculate the load the ice exerts on a structure in different modes of ice failure. Both IceDyn and IceFloe contain models that assume ice fails in its flexural mode as it rides up (or down) a sloped structure, like an ice cone. The force required to break a sheet of ice in bending is much less than the force required to break a sheet of ice in any other failure mode, making the flexural failure mode the ideal mode for ice to fail as it contacts an offshore structure. Substructures in the Great Lakes will likely be outfitted with a sloped ice cone at its waterline to induce this flexural failure mode as ice contacts the structure to exert the least amount of load on the structure. The primary limitation of IceDyn and Icefloe is that they cannot simulate the effects of ice ridges on an offshore structure, which is likely to be the design-driving ice load scenario for structures in Lake Erie. For potential Great Lakes Wind development, updates to these tools will have to be made or other calculation methods and models will need to be used to include the effects of ice ridges. Further data collection on the frequency and duration of ice ridge formation will also need to be completed to collect accurate properties and geometries of ice ridges. In parallel, for any Great Lakes Wind development outside of Lake Erie, these tools will need to be upgraded to include the effects of ice on floating substructures, or other tools will need to be used that account for floating considerations.

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PART II. Floating Substructure Recommendations

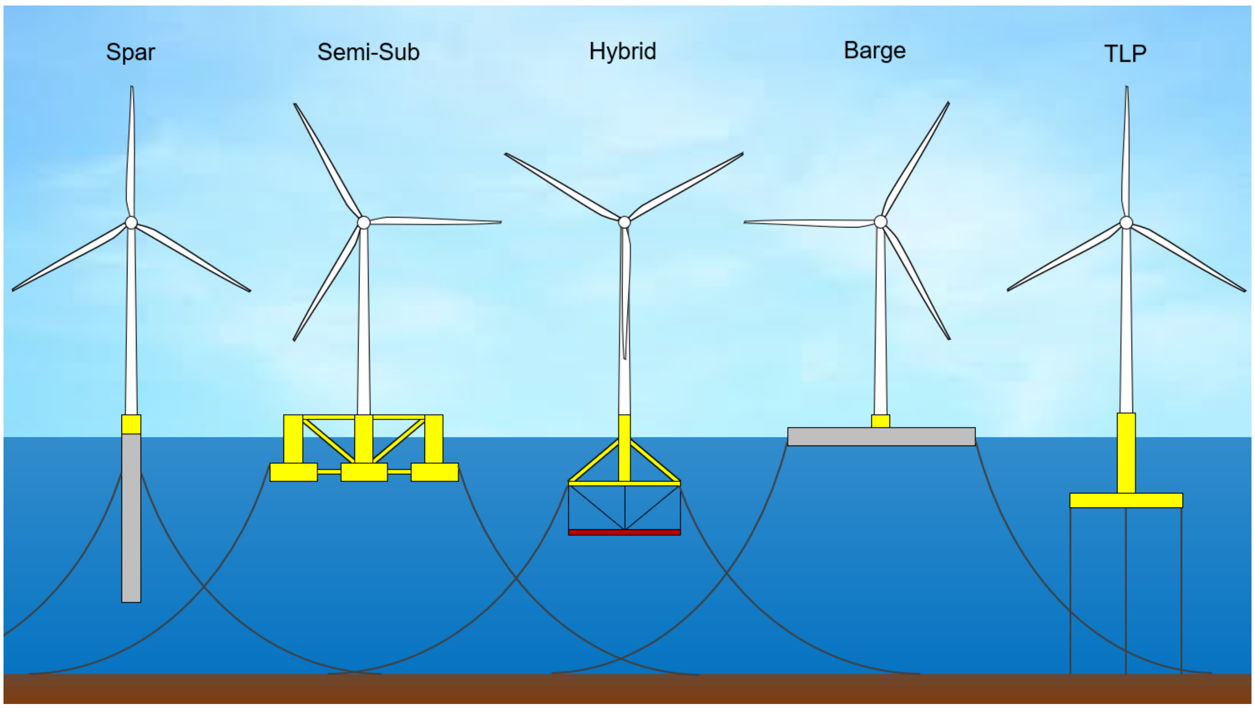
5 Floating Design Challenges and Drivers

Floating wind turbine technology has matured considerably in the last decade. As of the end of 2021, there has been a total of 123 MW of floating offshore wind installed capacity in the world (ABSG Consulting Inc. 2021). Floating support structures are used to support offshore wind turbines in water depths greater than 60 meters, where fixed-bottom support structures are no longer economically feasible (Musial et al. 2021). The objective of this report is to determine the feasibility of floating wind turbine substructures in the Great Lakes adjacent to the state of New York. Lake Ontario has the best conditions to support floating substructure technology due to its deeper waters, especially at distances farther from shore. Conversely, the relatively shallow waters of Lake Erie are not suited for floating wind turbines.

Similar to the fixed-bottom substructure types, the design of floating substructures and their station keeping systems are subject to a wide range of unique environmental characteristics, and some designs that are being deployed in ocean regions may not be feasible in the Great Lakes. Floating wind turbines can experience significant motions in response to wind, waves, and ice loading. Typically, the wind thrust force is the largest steady load on the system, and waves contribute the largest dynamic load on the system, both of which influence the sizing of the floating substructure and mooring system. The assembly of structural members of a floating substructure and the mooring system components are carefully designed to resist these expected loads on the system. In the Great Lakes, surface ice loading can impart significant loads as well, which become a primary consideration when assessing the feasibility of floating substructures for Great Lakes Wind.

There are many solutions that have been designed to support an offshore wind turbine in deep water. These solutions require the substructure to float since the water depth is too deep for rigid fixed-bottom substructure types. Common floating substructures used in industry are shown in Figure 8, however, the figure does not show a complete taxonomy of the potential floating substructure solutions for the Great Lakes. Private communications with multiple offshore wind substructure developers indicate that new floating substructure designs, customized for Great Lakes conditions, will be the preferred choice for future Great Lakes Wind project development. These new designs will compensate for the physical and logistical conditions of the Great Lakes, such as constraints imposed by ice loading and the supply-chain limitation of the narrow width of the St. Lawrence shipping channel.

Figure 8. Common Floating Wind Substructure Types Considered in Feasibility Study



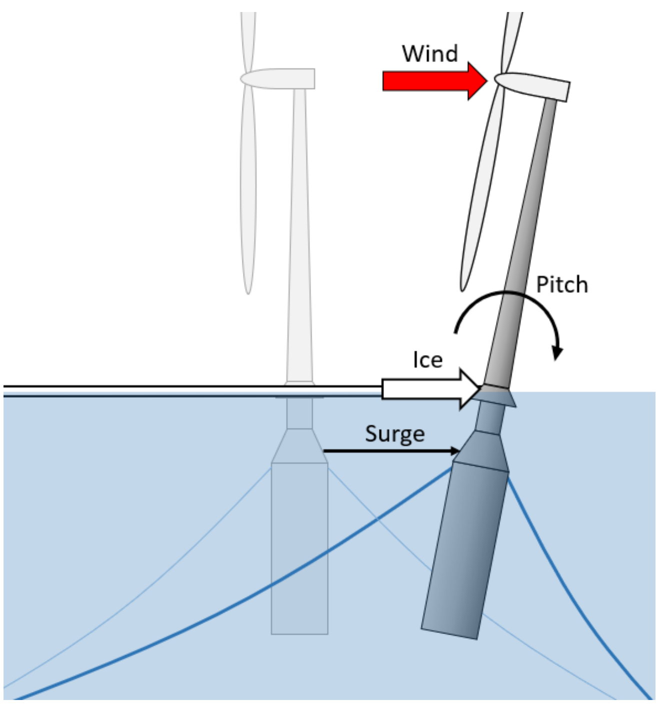
The presence of freshwater ice in the winter months of the Great Lakes poses the most significant environmental factor that differentiate wind turbines in the ocean and wind turbines in the Great Lakes. Lake level ice, which is any form of a flat ice sheet on a lake, has the potential to exert a force on the same order of magnitude as the wind on an offshore structure. As such, ice considerations will play a large role in sizing and selection of floating wind substructures and mooring system properties in the Great Lakes. A second environmental difference is the lakebed soil conditions of the Great Lakes. The soil conditions determine what anchor technologies can be used in the mooring system, which then determine what mooring configurations can be used. Lastly, the supply chain of the Great Lakes region has limitations on the development of Great Lakes Wind, which will need to be considered when determining the feasibility of different substructures. Generally, it was determined that floating offshore wind technology can be adapted to survive in the Great Lakes environment.

5.1 Ice Loads

Ice loads have the potential to be significant—and in some cases the largest—external forces on an offshore wind structure. Unlike fixed-bottom support structures, floating support structures can experience large displacements and noticeably large tilt angles in response to external loads. Because wind turbines have a limited tolerance for heel angles (typically around 4-5 degrees) and power cables have a limited tolerance for displacements, designing for ice loads may require significant adjustments to the floating platform, cable, and mooring system.

In the absence of ice, the largest steady force on a floating wind turbine is the thrust force of the wind. This force is resisted by the mooring and anchor system—the floating platform is displaced downwind by the thrust loading (surge), which increases tension on the upwind mooring lines until the net mooring system force balances the wind thrust force (Figure 9). Wave and current loading can also affect this balance, but is not as large as the wind loading. The change in mooring system tensions will cause a slight lowering (set down) of the platform in the water, on the order of 1–2 m. The load from wind-driven ice motion will directly add to these platform responses.

Figure 9. Floating Wind Turbine Ice Load and Offsets



The wind thrust force also results in a large overturning moment on the floating platform. For spar platforms, the moment arm is approximately the distance from the mooring line attachments to the turbine hub. This overturning moment causes the platform to pitch in the downwind direction until it is balanced by the hydrostatic stiffness of the platform (from waterplane area and/or ballast) and the mooring line tensions. The load from wind-driven ice motion will add to the overturning moment, albeit to a lesser degree because the ice load has a smaller moment arm. Meanwhile, during the colder months, the presence of level ice will practically eliminate waves, ostensibly eliminating the hydrodynamic excitation on the system. There will still be wave excitation on the system in the warmer months, but the loads from wind and ice during winter will be greater, making wind and ice the largest design-driving loads. A further order of magnitude quantification analysis is done below. Considering the above, the general implication of ice loads on floating wind turbine support structures is twofold: the mooring system should be strengthened to withstand ice loads and maintain displacement limits, and the system hydrostatic stability (whether through ballast, platform width, or mooring tension) should be increased to maintain pitch angle limits.

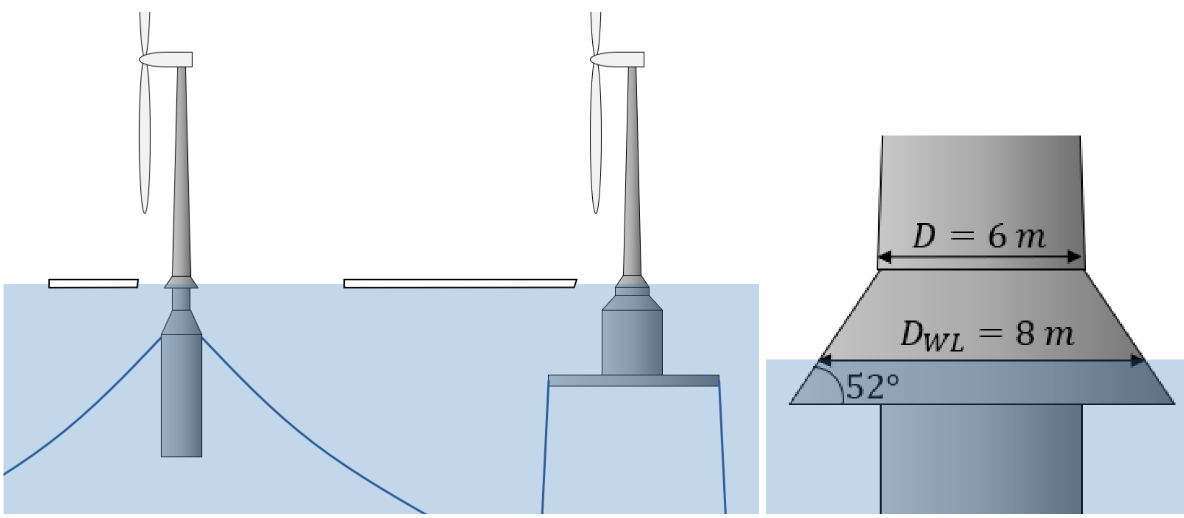
In concert, the magnitude of ice loads can be reduced using the ice cone techniques already discussed for fixed-bottom substructures in the *Fixed-Bottom Substructure Recommendations Report*. The use of ice cones is more complicated for floating wind turbines compared to fixed-bottom substructures. In ice-free conditions, a protruding conical geometry near the waterline will increase the amount of structure exposed to wave loads and thus increase the system loads and motions. The effect would be especially significant for larger wave amplitudes where a wave crest may reach the edge of the cone. The overall system hydrodynamic behavior will change due to the new conical geometry at the waterline, as opposed to the typical cylindrical geometry. In ice-covered conditions, waves are much less of a factor. However, the platform displacement from combined wind and ice loads will induce some set down, which changes the vertical position of the ice cone relative to the surface. Both these factors need to be considered when designing the ice cone.

Estimating the implications of the ice loads on a floating system design can be done by estimating the ice load magnitudes and adding them to the force balances that are used in a basic floating system sizing process. The historical maximum measured ice thickness in Lake Ontario is 40-50 cm (Sleator 1995) and according to the *Evaluation of Site Conditions Report*, the rarity of large amounts of ice cover in Lake Ontario makes ice ridges unlikely. Surface ice is also more likely near the shores than in the center of the lake where turbines are more likely. Therefore, the design-driving ice case is considered to be 50 cm thick level ice.

Two generic floating wind turbine support structure designs are used to estimate typical ice loads and the required changes in platform and mooring system sizing to support them. One is a spar, which has a deep draft with ballast for stability. The other is a tension leg platform (TLP), which uses high-tension vertical mooring lines for stability. Both designs are sized for the NREL 5 MW reference wind turbine in an assumed water depth of 80 meters (where water depths can reach 200 meters in the middle of Lake Ontario). The NREL 5 MW reference turbine was considered an accurate approximation for the scale and loading of a wind turbine that may be selected for GLW due to its model's accessibility, and because it is close in size to the 6 MW reference turbine used in this study. Both baseline designs (sized without ice loads) are given in Figure 10a, and both designs have the same slender profile near the waterplane with representative dimensions given in Figure 10b.

Figure 10. (a) Generic Spar and TLP Geometries; (b) Ice Cone Geometry on a Representative Floating Substructure

a) b)



Using the methods described in the *Fixed-Bottom Substructure Recommendations Report* for level ice and a method implemented in the ice modeling module IceFloe (McCoy 2014), the horizontal ice load on a level ice sheet characteristic of Lake Ontario can range from 0.4–0.7 MN for the assumed floating wind turbine cone geometry shown in Figure 10b. This geometry adopts the 52° cone angle from Allyn and Croasdale (Allyn and Croasdale 2016) with a tower diameter of 6 meters above the cone. A study of ice cone design variations for floating wind turbines is outside the scope of work but would be relevant to inform development of specific designs. Using an assumed fairlead depth of 20 meters on the spar and 30 meters on the TLP, the maximum overturning moment of the ice load is on the order of 14 MN-m, with the ice load moment arm as the distance from the free surface to the mooring line fairlead depth. Comparatively, the wind load on the NREL 5 MW reference turbine is 0.8 MN and an overturning moment on the order of 88 MN-m. These numbers are tabulated in Table 8. This expected design ice load represents a potential doubling of the horizontal load on the floating support structure and a slight increase in the total overturning moment.

Table 8. Environmental Loads and Moments on Representative Structure in Lake Ontario

Parameter	Spar	TLP
Horizontal Wind Load (MN)	0.8	0.8
Wind Overturning Moment (MN-m)	88	88
Horizontal Ice Load (MN)	0.7	0.7
Ice Overturning Moment (MN-m)	14	21
Total Horizontal Load (MN)	1.5	1.5
Total Overturning Moment (MN-m)	102	109

These changes in the system loads need to be counteracted by the floating substructure design and mooring system. The spar sizing is based on a maximum steady pitch angle of 4° and the TLP sizing is based on a tension variation of 33% of mean tension between four tension legs. The designs are then resized by changing their ballasting, mooring weights, and substructure diameters to achieve the same maximum offsets when ice loads are included. The values with and without ice and the relative changes in these properties are given in Table 9.

Table 9. Estimated Changes in Floating Support Structure Sizing to Support Ice Loads

Property	Spar			TLP		
	Without Ice	With Ice	% Change	Without Ice	With Ice	% Change
Horizontal load (MN)	0.8	1.5	88%	0.8	1.5	88%
Overturning moment (MN-m)	88	102	16%	96	117	22%
Substructure displacement (t)	9,550	10,200	7%	4,080	4,550	11%
Ballast weight (t)	6,550	7,150	9%	N/A	N/A	N/A
Mooring line strength (MBL)	Depends on configuration		88%	12.3	15.3	25%
Anchor capacity	Depends on configuration		88%	15.4	19.2	25%

The values in Table 9 represent order-of-magnitude estimates for the design changes required to withstand ice loads. For a spar configuration, keeping the same pitch limits in the presence of ice loads requires an estimated 7% increase in substructure displacement and 9% increase in ballast. For a TLP configuration, keeping the same offsets and tension margins requires a 11% increase in platform displacement. For both designs, the demands on the mooring lines and anchors almost double, in proportion with the total horizontal load. This will require an increase in anchor capacities to effectively resist the increased loads.

These estimates are intended as worst-case values for floating wind systems that are at risk of encountering the maximum level ice conditions in Lake Ontario. Installations in areas with lower ice thicknesses or ice cover probabilities could conceivably have smaller levels of ice reinforcement. The ice properties (thickness, velocity, etc.) measured and collected in Lake Ontario provide reasonable inputs to the ice modeling methods to calculate a maximum level ice load. The uncertainties of the worst-case scenario reside in any ice ridge or extreme ice event that a structure can encounter in Lake Ontario. There is not enough measured extreme data to make more accurate extreme ice load calculations. These judgements would be aided by more data collection and analysis of Lake Ontario ice conditions.

5.2 Soil Conditions

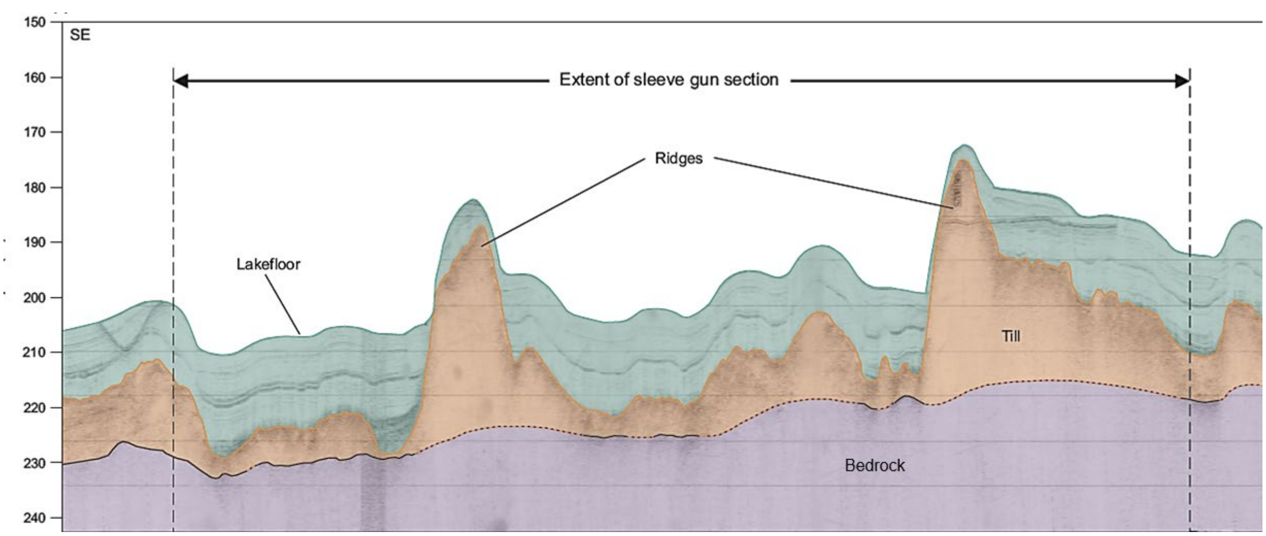
A second important design driver for a floating substructure design in the Great Lakes is the lakebed soil conditions. The soil conditions will not directly influence the substructure design, but will determine which anchor types are feasible in the Great Lakes, which will determine the mooring system and configuration. Between the two Great Lakes under consideration, Lake Ontario is the only lake likely to utilize floating substructures and mooring systems. Details on the specifics of Lake Ontario soils can be found in New York State Great Lakes Wind Energy Feasibility Study: Physical Siting Analysis (NYSERDA, 2022b), but the important points are summarized below in relation to their influence on anchor type design.

According to the New York State Great Lakes Wind Energy Feasibility Study: Physical Siting Analysis (NYSERDA 22-12b), Lake Ontario primarily consists of clay soils with small pockets of silt and sand dispersed throughout the lake. The depth of subsurface soils to bedrock is relatively shallow and only reaches a maximum depth of 25-30 meters and some areas have bedrock less than 10-15 meters below the subsurface. However, the minimum soil depth requirements for anchor embedment are generally shallower than for fixed-bottom piles, so most average soil depths were found to be acceptable.

Anchors for floating substructures do not require the same soil properties as foundations for fixed-bottom substructures do. Anchor geometries and penetration depths can be tailored to different soil types and stiffnesses. Most anchors have penetration depths less than 10 meters, which is shallow enough for most anchors to work in the soils of Lake Ontario. With an anchor selected for a floating substructure mooring system, the specific anchor adjustments can be made at the time of site development. Therefore, the primary variables with regard to lakebed soil conditions are not significant design drivers for floating wind, especially when compared to the higher sensitivity of fixed-bottom foundation to soil conditions.

In general, Lake Ontario's lakebed bathymetry is rougher and less consistent compared to Lake Erie, due to significant subsurface features like drumlins, which are geophysical landform deposits, or hills, that are a result of glacial movement in certain areas. Due to the nature of glaciation, the subsurface depth is highly variable in the middle of Lake Ontario. Figure 11 is taken from New York State Great Lakes Wind Energy Feasibility Study: Physical Siting Analysis (NYSERDA 2022b) as an example of the change in water depth in a cross section of Lake Ontario.

Figure 11. Cross Section Profile of Drumlins in the Rochester Basin of Lake Ontario



In this cross-section, the water depth varies between 175 and 210 meters in the middle of Lake Ontario between the ports of Oswego and Rochester. Careful consideration would need to be taken for how a mooring system would interact with the lakebed at a specific site in the presence of these geotechnical obstacles, and they may prohibit anchor placement in some areas. Because the presence of these drumlins is deterministic, they can be avoided with proper siting.

5.3 Local Supply-Chain Limitations

Local manufacturing plants and ports will need to be capable of supporting fabrication and assembly of floating substructure components that address the limits in transporting and shipping large components in and out of the Great Lakes region. The primary Great Lakes supply-chain limitation is the size of the vessel that can navigate through the locks along the St. Lawrence River. A vessel with the ability to install large substructure components is not likely to be able to navigate the St. Lawrence River, so the likely scenarios of installation are to use a float-out method of installation. Unlike fixed-bottom turbines, floating turbines can be fully assembled and commissioned at quayside, and towed out to the site with smaller vessels from a suitable port facility.

The scale of floating wind turbines in Lake Ontario is primarily limited by the capacity of the heavy lift cranes that can be brought in and integrated as part of the infrastructure of the designated marshalling port. The reference turbine for this study is a 6.0 MW turbine based on the conservative assumption that only cranes large enough to lift these turbines would be available. However, the availability of larger cranes with lifting capacities over 600 tons and crane heights over 150 meters would enable the 12 MW to 15 MW turbines that are being procured for offshore wind development in the Atlantic Ocean. These larger turbines would be more visible from shore, but for a given wind plant size, would lower the overall number of structures in the viewshed.

The floating substructure design selection will depend on the ability to adapt the port facility for substructure fabrication, quayside turbine assembly, loadout to site, and service. Full details of the supply-chain limitations can be found in New York State Energy Research and Development Authority (NYSERDA). 2022. “New York State Great Lakes Wind Energy Feasibility Study: Infrastructure Assessment. (NYSERDA 2022b).

6 Floating Substructure Type Feasibility Assessment

Most of the styles of floating wind substructures being considered for offshore wind in the ocean have been derived from the oil and gas industry. They include ballast-stabilized substructures, like spars, buoyancy-stabilized substructures, like semi-submersibles (semi-subs), and mooring line stabilized substructures, like tension leg platforms (TLP). Hybrid substructures, like the TetraSpar ("The TetraSpar full-scale demonstration project" n.d.), and floating barges were also included in the first assessment. In general, floating substructures may eventually become easier to manufacture, install, and decommission relative to fixed-bottom substructures, but more complexities may arise on a floating platform due to the coupled motions of the platform. Because they are decoupled from the lakebed, turbine installation and assembly of the substructure can typically be conducted in a berth at the port where working conditions are easier to control and labor costs are lower. It is assumed that the fully commissioned turbine and substructure can be towed out to the site for connection with the mooring system. Similarly, the platform can be disconnected from the mooring system and towed back to port for maintenance or decommissioning. More details on the GLW-specific installation and assembly considerations can be found in New York State Energy Research and Development Authority (NYSERDA). 2022. "New York State Great Lakes Wind Energy Feasibility Study: Infrastructure Assessment, (NYSERDA 2022b).

6.1 Floating Substructures

6.1.1 Spar

Spars are long, slender, ballast-stabilized, cylindrical structures that have a small waterplane area and a large ballast mass with a low center of gravity to minimize heave and pitch motions that result from the environmental loads (first from the left in Figure 8) (Jiang 2021). The submerged weight from the ballast lowers the center of gravity of the structure, which increases the overall stability of the platform and helps resist the overturning moments from the environment (Kopp 2010). The world's first floating wind farm, Hywind 2 in Scotland, utilizes spars that have a 90-meter draft, a 14.4-meter diameter, and weigh 3,500 tonnes each ("Floating Offshore Wind in Equinor - Equinor.Com" n.d.). They utilize suction piles as anchors with a diameter of 5 meters, a length of 16 meters, and a weight of 111 tonnes. The total height of the turbine and substructure can be up to 258 meters, which means that spars require more vertical port space for construction relative to other floating substructures.

Spars are typically constructed onshore and floated out horizontally to a sheltered area to be upended by ballast and have the wind turbine installed using a heavy-lift crane vessel. It is then towed out to the installation site to hook up to the mooring system (Jiang 2021). They require a significant amount of steel or concrete to manufacture, which would require the proper manufacturing infrastructure. New methods to improve the installation process and enable turbine and spar assembly in standard port facilities are currently in development, because most areas of the world are not suitable for offshore wind spar construction and installation (Jiang 2021). One proposed installation method is to construct the substructure horizontally with the turbine attached in a near-horizontal position and towed out to a depth where the entire support structure can be upended and ballasted. This is referred to a tilt-down spar, but has been discouraged due to the high bending moments on the tower due to the hanging weight of the turbine in the horizonal position.

Spars can only be viable solutions for floating substructures in Lake Ontario if there was a proven and developed installation method for the shallow port depths of the Great Lakes. Currently, the port depths in Lake Ontario are on the order of 5-10 meters, which is not deep enough to upend expected spar lengths on the order of tens of meters. New installation procedures would have to adapt to these Great Lakes installation constraints for spars to be feasible. Otherwise, spars could be compatible with ice loading if outfitted with ice cones, given that it only has one member piercing the waterline with a relatively small waterplane diameter. The manufacturing of the large, steel cylinder of a spar is not currently done in the Great Lakes region, but this production capability would need to be developed. Lastly, spars would have low costs compared to other substructures, which would add to their overall feasibility. Generally, spars will not be suitable for Great Lakes Wind because of the difficulty of quayside assembly.

6.1.2 Semi-Submersible

Semi-submersibles (semi-sub) (second from the left in Figure 8) are substructures with three or four large, buoyant vertical columns and sometimes one column in the middle connected with various cross-members. They have lower drafts than spars but higher waterplane areas for better hydrodynamic stability and higher structural stiffness against wave loads (Jiang 2021). During the winter months in the Great Lakes, the high waterplane areas and complex waterline-piercing cross members would likely cause high and complex ice jamming loads on the support structure. Once constructed at port or onshore, they are easily towed out to an installation site, allowing for simple installation and decommissioning using only tugboats (Jiang 2021). They are the most common substructure type proposed for floating offshore wind but are not considered suitable for Great Lakes wind because the large amounts of structure at the waterline makes them incompatible with the lake ice.

6.1.3 Tension Leg Platform

Tension-Leg Platforms, or TLPs (first from the right in Figure 8), are vertically moored, submerged, buoyant platforms that use high-tension mooring lines to stabilize platform motion. They come from the oil and gas industry, but substructure designs for wind turbines are smaller than oil and gas applications and lighter than other floating platforms. The mooring lines carry high vertical tensile loads to the anchors, which results in higher stability and less motion overall compared to other types of floating substructures (Kopp 2010). The vertical tendons are typically connected to substructure members that extend radially by 20- to 30-meters, and the vertical geometry results in the lowest mooring footprint of any substructure type (Jiang 2021). Most of the TLP structure is submerged below the level of ice floes, which means TLPs are likely to handle ice loads well since they only have one relatively slender member crossing the waterplane, with no potential for ice jamming.

Like most floaters, TLPs would need to be assembled in port and towed out to the installation site. However, they are not stable with the turbine installed, so the assembly either needs to be on-site, or supplemental buoyancy solutions are needed, such as adding temporary buoyancy modules during float-out, or ballasting accordingly before and after connecting to the mooring system (Fernández 2010). Any of these installation procedures would involve easy connection to the mooring system and disconnection for maintenance purposes (Fernández 2010). Common anchor solutions for TLPs include suction piles (Wu et al. 2019), which are suitable for soft clay and varying depths, or vertical-load anchors (VLAs). However, they are less common because of complexities that arise from the high-tension anchoring and mooring system, and concerns that tendon failures could become catastrophic.

TLPs may be suitable for Great Lakes Wind if the buoyant substructure is submerged below the level of the ice floes and only the slender tower section pierces the waterline. For Lake Ontario, this would avoid the complex ice loads that arise from ice jamming, but they would still need to be outfitted with ice cones. The primary challenge of the TLP is that they are inherently unstable until the tendons are attached to the lakebed, making quayside assembly and commissioning at port difficult. TLP’s could be developed for Great Lakes wind if a secondary buoyancy rig were developed to stabilize the system during assembly, commissioning, and loadout, and then removed after the tendons were secured. The installation procedure would have to account for the draft of the substructure, the secondary rig, and channel depth. Besides the installation and waterplane adaptations, the manufacturing of TLPs would need to be established in the Great Lakes region with reasonable investment. The other big challenge would be the development of a suitable vertical load anchor system that could work in the soils of Lake Ontario. Overall, the low mooring footprints and other advantages of TLPs could provide a feasible solution for a floating substructure in the Great Lakes.

6.1.4 Hybrids

There are other substructures that may not exclusively fit into one of the previous three categories, or have the attributes of multiple substructures during different phases of assembly, deployment, and operation. One representative example of a "hybrid" substructure (third from the left in Figure 8) is the TetraSpar ("The TetraSpar full-scale demonstration project" n.d.). The TetraSpar (Figure 12) is a tetrahedral shaped substructure with supports connecting each corner of the main substructure to the bottom triangle section, called the keel. The members of the substructure were designed to not be larger than the turbine components to facilitate transportation and fabrication of the subcomponents. The keel can be ballasted for towing purposes and help float the structure like a semi-sub to be towed out to the site without the need for an installation vessel (Jiang 2021).

Figure 12. The TetraSpar Hybrid Substructure

All that is required to assemble the TetraSpar substructure and turbine is a port 8-10 meters deep and a quayside berth with adequate crane capacity; it needs no specialized equipment ("The TetraSpar full-scale demonstration project" n.d.). It can be launched and ballasted to float or loaded onto a submersible barge, like a semi-sub, and the turbine can then be installed using land-based cranes rather than heavy lift vessels. Once towed or barged to the site, the substructure can be attached to the mooring system and ballasted accordingly to lower the center of gravity, like a spar (Jiang 2021). The conventional TetraSpar's waterline profile includes multiple waterplane-piercing cross-members, which will likely lead to undesirable ice jamming loads. However, the substructure design can adapt to Great Lakes conditions and alter the braces that connect to the central column to connect below the waterline, as well as be outfitted with an ice cone. These adaptations will induce lesser and more favorable ice loads on the structure, and the unique design and assembly instructions can overcome the low port depth requirements of Lake Ontario and allow efficient float-out to the site. The TetraSpar is a relatively new design, as are most floating wind designs, but its novelty should not lower its feasibility for Great Lakes Wind.

6.1.5 Barges

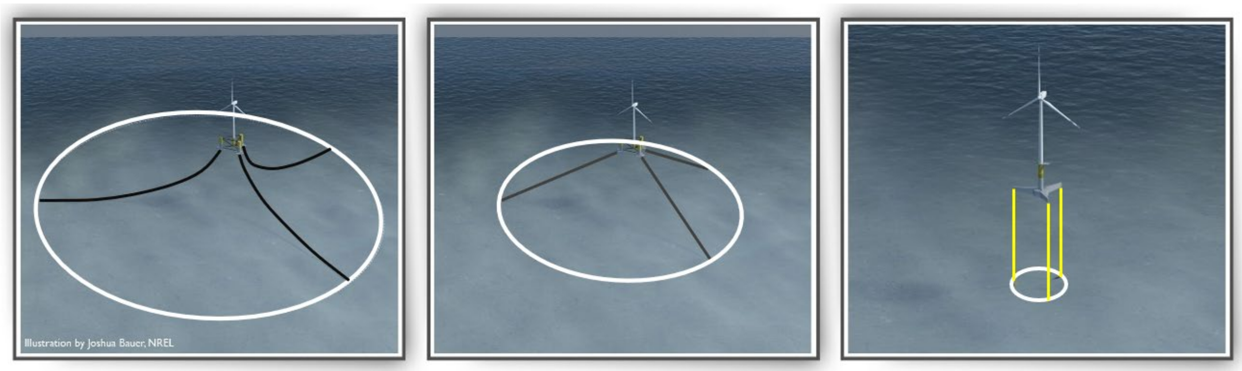
Barges (second from the right in Figure 8) are wide, flat structures with small drafts and large waterplane areas. The low drafts of barges allow for easy assembly of the wind turbine and substructure at port. Their simplicity would allow them to be easily manufactured locally. However, the large amount of structure at the waterline would make them extremely vulnerable to ice loads and could cause undesirable motions of the turbine. Therefore, barges are not considered suitable for Great Lakes Wind.

6.2 Mooring and Anchoring

6.2.1 Mooring

In floating offshore wind turbine applications, there are typically three general types of possible mooring system configurations: a catenary configuration, a semi-taut configuration, and a vertical tendon configuration (typically used for TLPs) (Figure 13). Catenary mooring systems are simple to install but difficult to maintain. Their footprints are the largest and the mooring line that contacts the lakebed is the most susceptible to wear and corrosion. Semi-taut mooring systems provide potentially lighter and stronger moorings, with the restoring forces coming from the elasticity in the synthetic rope mooring line, but have more difficult installation and maintenance procedures and would require specific anchors to handle the semi-tautness of the system. Vertical tendon configurations are mainly used for TLP substructures with very small footprints, very high mooring tensions, and would also require more advanced installation and maintenance techniques.

Figure 13. Catenary, Semi-taut, and Vertical Tendon Mooring Configurations



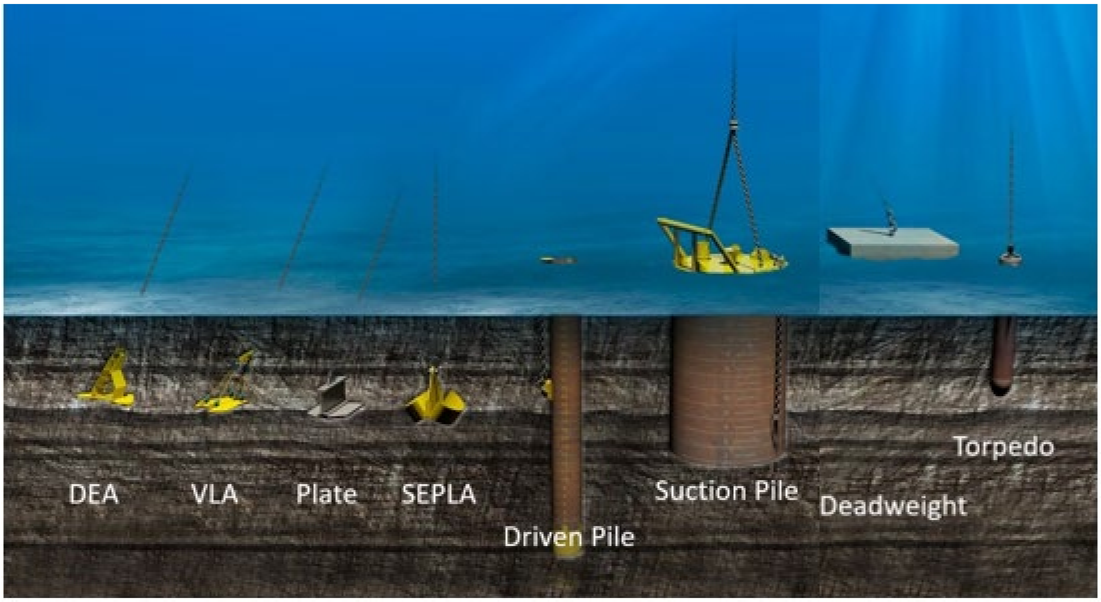
For each configuration, there are three main categories of mooring line types: chain, wire rope, and synthetic rope. Chain mooring lines are the most widely used line type material, manufactured in multiple shapes and sizes, and are more suited for contacting the lakebed due to their weight and abrasion resistance properties. Wire rope mooring lines are also available in many shapes and sizes, have the same breaking load and elasticity properties as chain, are lighter than chain, but are more likely to be corroded and damaged. Synthetic rope is the more recently developed mooring line type with high strength to weight ratios, near neutral buoyancy, high elasticity, corrosion resistance, and can be relatively more cost-effective. Rope saves cost by reducing mooring system weight in deep water, or by providing unique stationkeeping properties in shallow water. Some common synthetic rope types include polyester, nylon, polypropylene, Aramid, and HMPE (High Modulus Polyethylene). However, synthetic lines can add complexities to the floating structure’s motions due to the nonlinearities of the material and can be more expensive. Other than the mooring lines and the anchor, the mooring system can include other components, such as clump weights or buoyancy modules, to provide improvements in system weight and stationkeeping properties, but can add other load complexities. Many other advancements in mooring system technology are being developed to improve the stationkeeping performance and cost of floating systems. Mooring configurations with nonconventional line types and various combinations of clump weights and buoyancy modules are being researched and tested for various shallow and deep water applications. Stronger and cheaper anchor concepts are also being developed to effectively hold the anchor loads from the mooring system. All current and future types of mooring systems are initially considered suitable for Great Lakes Wind, but the specific details of the mooring configurations and components will be dependent upon the site characteristics, substructure type, and environmental loads of a given project.

Design requirements and considerations for mooring lines and systems for a floating offshore wind turbine include stationkeeping requirements in extreme conditions, hazards on the lakebed, tides, fatigue strength, corrosion, environmental impacts, power cable integrity, anchor failure, and recreational marine activities. There are also notable risks involved with the failure of a mooring line or system, in any configuration. Depending on the specific substructure or mooring configuration, one failure can cause failures in other parts of the mooring system. It can also exert undesirable loads and consequent motions on the platform, as well as an increase in load on the other intact anchors. Line and anchor maintenance before and after a failure has the potential to impact wildlife and the lakebed environment. In the event of a line failure, a mooring system with taut, synthetic rope mooring lines will likely be able to keep the floating platform within allowable offsets, however, it may be easier to reattach and anchor a new catenary chain mooring line. Each of these design requirements and failure risks need to be considered when designing and installing a mooring system that could be suitable for the Great Lakes.

6.2.2 Anchors

There are a range of anchor types that can be used in a mooring system. The four most well-known anchor types are deadweight anchors, drag embedment anchors (DEAs), pile anchors (driven and suction), and plate anchors ("Advanced Anchoring and Mooring Study" 2009; API RP 2SK 2005; Ma et al., n.d.). Other common types or variations include vertical-load anchors (VLAs), gravity anchors, and helical screw piles. Most of these anchor types are shown in Figure 14.

Figure 14. Anchor Types for Floating Offshore Wind Turbine Mooring Systems



The specific anchor selection for a mooring system depends on a multitude of factors, including the floating substructure type, the substructure's compatibility with a mooring system, the mooring configuration, soil conditions, the expected embedment depth, mooring line tensions, the anchor holding capacity, installation plans, and cost. The following describes common anchors in more detail.

Drag-embedment anchors (DEAs) come in many shapes, sizes, and orientations to accommodate various load capacities and soil conditions (first from the left in Figure 14). The geometry of a DEA allows for high horizontal capacity from the resistance of the soil, but no vertical uplift capacity. This means that they are primarily used in catenary mooring configurations, since the other configurations include vertical mooring loads. The horizontal load capacity is dependent on the anchor geometry, penetration depth, and soil friction conditions, which can be difficult to predict. They are installed easily by dragging along the lakebed until sufficient penetration to a desired depth is achieved, which is done primarily in soft soils, since they are harder to sink in sand and stiff clays. The range of penetration depths and drag distances will vary based on the DEA geometry and lakebed soil conditions, but a likely drag distance for a Great Lakes mooring system would be on the order of 50-100 meters. The installation process would also have a relatively low environmental impact based on the geophysical data of the region. DEAs provide a well-studied and relatively cheap and efficient anchoring solution, but they only have a unidirectional capacity, they do not perform well in hard lakebed soils, and usually have large mooring footprints. They are recoverable depending on the soil type, anchor geometry, penetration depth, and recovery angle, but harder to accurately place during installation.

Pile anchors come in two main types: driven-drilled-grouted piles, or suction piles. Both types of piles come in many shapes and sizes to provide great lateral and vertical load capacity and are more commonly found in semi-taut mooring configurations with smaller footprints. **Driven piles** (fourth from the right in Figure 14) typically have smaller diameters and require loud, expensive, and specialized pile driving installation equipment to drive, drill, and grout the anchor into the lakebed, which works well in harder lakebed soils. They have greater vertical uplift capacity, but the drilling and grouting process is expensive relative to other anchor types and may be more disruptive to the lakebed environment. The vertical load capacity depends on the pile's dimensions, installation characteristics, and soil conditions. The horizontal capacity can be altered by adding elements, such as a skirt to the top of the pile, to change the soil-structure interaction and provide lateral stiffness accordingly.

Suction piles (third from the right in Figure 14) are well-suited for deep water mooring systems and require specialized equipment for installation, but the pile driving process does not produce noise like the driven piles. The suction pile typically has an open bottom end to penetrate the soil and a closed top end to allow a pressure difference between the inside and outside of the pile and sink the pile into the lakebed. They are usually shorter and wider than driven piles (smaller suction piles are called caissons, which are shown second from the right in Figure 14; the length-to-diameter ratio will depend on the soil conditions) and provide better mooring integrity. Suction piles can be tailored to the specific environment to provide high lateral capacity, can be easily assembled, installed, and removed, and can be more cost-competitive relative to other anchor types. However, when taut moorings are attached to the pile anchors, they can produce unwanted complexities in the substructure's motions and mooring tensions, which can increase costs significantly in deeper waters and would require special equipment to maintain mooring connections.

Plate anchors are designed with a surface perpendicular to the mooring load direction and can be installed deeper in the lakebed to anchor mooring systems, which are typically semi-taut systems (third from the left in Figure 14). They typically have a relatively more involved installation process to embed the plate in the lakebed, either by driving the plate or sinking the plate with the aid of a suction pile, or embedding the plate by dragging it along the lakebed. The plate is then "keyed" so that it is oriented perpendicular to the direction of the mooring load. Similar to DEAs, this penetration depth and drag distance will vary based on the plate geometry and soil conditions, but a likely drag distance would be on the order of 50-100 meters, with a relatively low environmental impact. Once embedded, they have very high lateral and vertical load capacities and are more efficient than other anchors in terms of their capacity-to-weight ratio. They have a low environmental impact, a low mooring footprint, and can work in soft and hard lakebed soils. However, they are susceptible to strength reductions in taut mooring configurations, are usually not recoverable, are susceptible to abrasion and fatigue, and the surface installation vessel needs to always maintain position during installation. One variation of a plate anchor is a vertical-load anchor (VLA) (second from the left in Figure 14) that is similar to a plate anchor or a DEA in terms of installation, but provides higher load capacities in the vertical direction, which makes them useful for tendon moorings in TLPs. VLAs work well in soft clay or layered soil but are not recommended for sand and stiff clay. The deeper the penetration depth, the higher their capacity.

A common plate anchor used in industry is the suction embedded plate anchor (SEPLA) developed by InterMoor. This anchor uses the installation process of a suction pile to embed a plate anchor vertically and then key the plate anchor to become perpendicular to the mooring load. This anchor is most suitable for soft clay soil types in a semi-taut mooring configuration. It does have a longer installation time than other anchors, but the longer installation times produce more precise anchor placements. It requires large transport vessels, but does not require large deck space, since there would only be one suction follower that can be used for all plate anchors.

Deadweight anchors (Gravity anchors) are one of the simplest and most reliable anchor types (second from the right in Figure 14). They are typically simple-geometry anchors that are easy to manufacture, have easy mooring connection points, have low mooring footprints, and can sit on thin sediments of the lakebed. They are the most economical if low cost material is readily available and are simple to construct on-site. However, their capacity is proportional to its mass, so their size is limited by the available installation equipment. Because of this, the lateral capacity is usually low, reducing the usable water depth, which is not favorable for most floating wind applications. Therefore, deadweight anchors are rarely used due to their limited capacity, but may be useful if the lakebed cannot be penetrated.

Dynamically embedded anchors, which are a form of gravity anchors, are a less common anchor solution but can still be a viable option in certain conditions. A common example of a dynamically-embedded anchor is a torpedo anchor (first from the right in Figure 14), which uses the kinetic energy from a free fall from the water surface to penetrate the lakebed. Therefore, the installation time is very low and provides a quick, economical anchor solution that has good lateral and vertical load capacities suitable for catenary and semi-taut mooring configurations. The vertical and lateral capacities are determined by the embedment characteristics, such as anchor weight, penetration depth, and soil conditions. They are most suitable for soft to medium clay conditions and are more commonly found in smaller, shallower mooring systems.

Other variations of the general anchors listed above have been designed to combat some disadvantages of certain anchors. **Screw piles (or helical piles)** utilize a number of circular plates in the shape of a screw to provide high tensile loading capacity in multiple soil conditions and have relatively quiet installation procedures. However, the technology of helical piles is not as developed as existing anchors and will require further field trials (Byrne and Houlsby 2015). **Micropiles** (or mini piles, needle piles, or root piles) distribute the anchor load into multiple small-diameter (on the order of inches) steel bars where each bar has an installation procedure similar to a driven-drilled-grouted pile. Engineering judgement and the site-specific conditions and characteristics should be used to determine which anchor to use for a given project.

Each anchor type is more suited for certain soil types and less suited for others. The most common soil types found in offshore wind waters are sand and clay, but there can also be instances of gravel, cobbles, boulders, and rock depending on the location. Table 10 categorizes the soil compatibility for each anchor. A blue color denotes that the anchor type functions well for that soil type, a purple color denotes that the anchor type can function in that soil but would require certain modifications, and a black color denotes that the anchor type does not function well for that soil type.

Table 10. Soil Suitability for Different Anchor Types

Source: "Advanced Anchoring and Mooring Study" 2009

Soil Type	Deadweight	Drag	Pile	Plate
Soft clay, mud				
Soft clay over hard layer				
Stiff clay				
Sand				
Hard glacial till				
Boulders				
Soft rock				
Hard rock				

Blue: functions well, Purple: functions, but not the best choice, Black: does not function well

The primarily clay soils of Lake Ontario would likely be able to support any of the four main anchor types listed in Table 10. The relatively shallow depth to bedrock of Lake Ontario should not be a limiting factor for any anchors, but should be a factor to consider in any future project site planning. The roughness of the lakebed of Lake Ontario and the consideration of subsurface features like drumlins, however, will likely make certain DEAs and plate anchors difficult to install in certain areas, since they would need to be dragged through the lakebed and the lakebed depth can vary on the order of 10's of meters over a small area. These areas can be avoided during the project planning phase. The high variations in local water depth can make mooring configurations with shorter lines on the lakebed and a smaller footprint more attractive, like a semi-taut or vertically-moored mooring configuration. Suction pile anchors could be well-suited for the clay soils in most of Lake Ontario, whereas driven-drilled-grouted piles are feasible, but would likely require expensive installation equipment that may be difficult to access in the Great Lakes. Certain VLAs, plate anchors, dynamically-embedded gravity anchors, and helical anchors would have no limiting factors and also be well-suited for the given soil conditions.

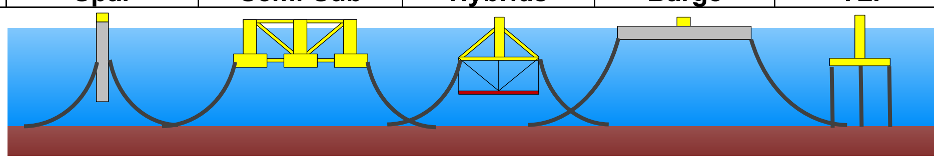
6.3 Substructure Feasibility

Considering the design challenges and drivers of floating wind technology in the Great Lakes, a feasibility assessment was performed to determine the suitability of each of the floating substructures described in the previous sections in the Great Lakes with the assumption that floating substructures would be more suited for Lake Ontario compared to Lake Erie. Each substructure type was evaluated on five different criteria and rated according to whether it would be feasible to install in the Lake Ontario.

1. **Installation Ability** is assessed based on the support structure's potential to be compatible with local port facilities to enable to use of float-out installation methods or available lake vessels for installation, commissioning, and service.
2. **Ice-structure Interaction** is based on the substructure's ability to achieve a slender waterline profile.
3. **Local Manufacturability** is based on the potential to adapt the substructure for manufacturing in the Great Lakes region, including the Northeast U.S. and the Midwest.
4. **System Cost** is evaluated based on the substructure's ability to minimize the cost of all parts of the design process considering the primary design challenges and constraints of Lake Erie.
5. **Technology Readiness** is an assessment of the risk associated with a support structure's maturity within the global industry and degree to which it can be fully commercialized.

The results of the feasibility assessment are qualified in Table 11. Lakebed compatibility, which was used as a criterion for fixed-bottom substructures, is not used in this diagram since the compatibility is based on the mooring and anchoring solution, rather than the substructure. The feasibility of specific anchor types is done in the previous section. The ratings for each substructure for each criterion are either “red”, “yellow”, or “green”. A “red” box indicates that a substructure has a major limiting factor for that criterion. A “yellow” box indicates that a substructure is feasible for that criterion, but significant challenges remain. A “green” box indicates that in general, the substructure fits that criterion and is a preferred solution.

Table 11. Feasibility Assessment of Floating Substructure Types

Floating Criterion	Spar	Semi-Sub	Hybrids	Barge	TLP
					
Installation Ability	Red	Yellow	Green	Green	Yellow
Ice-Structure Interaction	Green	Red	Green	Red	Green
Local Manufacturability	Yellow	Yellow	Green	Yellow	Yellow
Overall Cost	Green	Green	Green	Green	Yellow
Technology Readiness	Green	Green	Yellow	Yellow	Yellow

From this qualitative assessment, the substructures with a major limiting factor are spars, semi-subs, and barges. As stated previously, current installation procedures for spars would prove to be incapable in Lake Ontario due to the low water depths at port. A similar statement can be made for semi-subs and TLPs, but to a lesser degree since the drafts of semi-subs and TLPs are much less than spars. The second main limiting factor, which applies to semi-subs and barges, is the ice-structure interaction. Semi-subs have multiple legs that pierce the waterline and barges have large waterplane areas, which both contribute to high and undesirable ice loads. TLPs and hybrids can also contain multiple water-piercing members, but there are easier methods, such as connecting those members to the center column below the waterline, to reduce the ice loads on the structure.

The remaining substructures—hybrids, like a TetraSpar, and TLPs—were determined to have no major limiting factors to be deployed in Lake Ontario. Both can have slender waterline profiles and the ability to be outfitted with an ice cone. Both have relatively easy installation procedures that can work in ports of Lake Ontario. They both have potential to be manufactured in the local Great Lakes region and their costs and technology readiness's will be dependent on the future supply-chain. TLPs are a well-developed technology used by the oil and gas industry, which should be able to transfer over well to the offshore wind industry, and the first TetraSpar substructure was deployed in 2021 off the coast of Stavanger, Norway.

7 Ice Floe Modeling for Floating Systems

For potential future floating technology development in the Great Lakes, the modeling and simulation tools should have the ability to analyze floating offshore structures exposed to ice. The open-source ice modeling modules, IceDyn, and IceFloe, that are part of NREL's OpenFAST suite, were written with the assumption that the substructure was fixed to the lakebed. Both modules require a SubDyn input file to run, which is an input file to OpenFAST that describes the substructure characteristics. SubDyn input files for floating substructures are possible, but there are not any tested files currently available. There are ongoing projects that use SubDyn input files for floating substructures in OpenFAST, but none are developed enough to accurately investigate ice loading. Even so, the existing ice modules would not be able to account for the additional challenges related to the dynamics of a moving floating structure interacting with ice.

Other than IceDyn and IceFloe, the capabilities of floating technology to resist ice loading conditions have benefited from increased experience from Arctic exploration. SBM Offshore is one company that has performed projects using floating bodies in these types of ice environments (Figure 15).

Figure 15. SBM Offshore Floating Structure Exposed to Ice

Source: SBM Offshore

A program partnered with the Norwegian University of Science and Technology (NTNU) and industry, Sustainable Arctic Marine and Coastal Technology (SAMCoT), has performed extensive research on ice and its effect on offshore structures ("Final Report SAMCoT 2011-2019," n.d.). As a result, Arctic

Integrated Solutions AS (ArcISo), a new company branching off of NTNU, has developed a software package for modeling ice and offshore structures using SAMCoT's numerical models, called Simulator for Arctic Marine Structures (SAMS). This program can simulate the ice-structure interaction for floating substructures in an Arctic environment. One study was able to use a numerical ice model to simulate the ice-structure interaction of a floating spar-type platform using the aero-elastic-servo-hydro simulation tool HAWC2 (Horizontal Axis Wind turbine simulation Code 2nd generation) (Shi et al., 2018). The study simulated a fixed monopile substructure, as well as a floating spar substructure, and the ice loads from the spar were found to be less than the ice loads for the monopile due to the significant motion of the floating wind turbine.

There are efforts and capabilities in other parts of the world to model and simulate floating structures in cold-weather environments, but none so far in the NREL OpenFAST suite. Significant investment will be needed to accurately model and simulate the effects of a floating wind turbine structure interacting with ice. We recommended that these investments be made to investigate the behavior of a floating offshore structures under various ice loading conditions and then implement those new effects to the engineering simulation tools.

8 Timeframes for Commercial Deployment

Floating wind technology is in a pre-commercial stage with active research, development, and deployment of pilot and demonstration-scale projects in Europe, Asia, and North America. The scale of floating wind installations continues to grow. The first demonstration project in the U.S. (VolturnUS) was a 20-kW small-scale pilot in 2013. In 2021, the 50-MW Kincardine floating wind farm was completed off the shore of Scotland. Globally, commercial-scale projects are expected to begin installation as soon as 2024 (Musial et al. 2021).

Several of the substructure types described in Section 6 have been installed at pilot or demonstration-scale projects, while other types are in development (Table 12). Lessons learned from the initial floating wind projects as well as from the offshore oil and gas industry can inform the development of these new substructure types. The TLP is one example of a technology that is considered mature in the oil and gas industry but has not yet been demonstrated on wind turbines. Table 12 highlights spars and semisubmersibles as the substructure types with the most installations to date. Demonstration projects using spars have taken advantage of sheltered deep water assembly locations and heavy lift vessels capable of lifting a fully assembled wind turbine, which are not available on the Great Lakes. Deployment of spars on Lake Ontario could become more feasible by 2030 if alternative assembly methods (see e.g., Jiang, 2020) can be successfully demonstrated. As discussed in Section 6, the semisubmersibles that have been installed to date have a large structural profile at the waterline that would be susceptible to complex ice loading. However, customized hybrid designs that benefit from developers' experiences with semisubmersible platforms may be the most likely support structure for the Great Lakes in the next decade. A hybrid design suitable for the Great Lakes would not require any new technology but would have design features specified to avoid the major challenges of ice loading and port access. One example of a hybrid design, a TetraSpar demonstrator with a 3.6-MW wind turbine, began operation in the second half of 2021 (Buljan, 2021). Communication with Stiesdal Offshore Wind indicates that a modified TetraSpar concept that addresses surface ice loading is underway. Other developers contacted for this project have indicated similar plans to engineer floating wind energy systems that can survive ice floes.

Based on global industry market research and trajectories, and leveraging the expected project development of fixed-bottom and floating substructures in Europe and Asia, fixed-bottom and floating substructures suitable for the Great Lakes will likely become commercially available by 2030 and 2035, respectively.

Table 12. Floating Offshore Wind Substructure Design Concepts and Development Stages

Source: ABS Group, 2021

Type	Concept	Development Stage
Spar	Hywind	Installed
	Toda Hybrid Spar	Installed
	Fukushima FORWARD Advanced Spar	Installed
	SeaTwirl	Installed
	Stiesdal TetraSpar	Installed
Semisubmersible	WindFloat	Installed
	Fukushima FORWARD compact semisubmersible	Installed
	Fukushima FORWARD V-shape semisubmersible	Installed
	VolturnUS	Installed
	Sea Reed	Under development
	Cobra semi-spar	Under development
	OO-Star	Under development
	Hexafloat	Under development
	Eolink	Under development
	SCD Nezzy	Under development
	Nautilus	Under development
	Tri-Floater	Under development
	TrussFloat	Under development
Barge	Ideol Damping Pool barge	Installed
	Saitec SATH (Swinging Around Twin Hull)	Installed
TLP	SBM TLP	Under development
	PivotBuoy TLP	Under development
	Gicon TLP	Under development
	Pelastar TLP	Under development
	TLPWind TLP	Under development
Multi-turbine platform	Hexicon multi-turbine semisubmersible	Under development
	W2Power	Installed
	Floating Power Plant	Installed

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17 Columbia Circle
Albany, NY 12203-6399

toll free: 866-NYSERDA
local: 518-862-1090
fax: 518-862-1091

info@nyserda.ny.gov
nyserda.ny.gov