New York State Great Lakes Wind Energy Feasibility Study: Cost Analysis

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NEW YORK STATE | NYSERDA

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New York State Great Lakes Wind Energy Feasibility Study: Cost Analysis

Final Report

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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, cost analysis

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Acronyms and Abbreviations

AEP	annual energy production
CapEx	capital expenditures
COD	commercial operation date
D	wind turbine rotor diameter
FCR	fixed charge rate
FLORIS	FLOw Redirection and Induction in Steady State (model)
FORCE	Forecasting Offshore wind Reductions in Cost of Energy
HVAC	high voltage alternating current
IEA	International Energy Agency
LCOE	levelized cost of energy
MACRS	modified accelerated cost recovery system
MW	megawatts
NCF	net capacity factor
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
O&M	operations and maintenance
OpEx	operational expenditures
ORBIT	Offshore Renewables Balance-of-system Installation Tool
ORCA	Offshore Regional Cost Analyzer
U.S.	United States
WTIV	wind turbine installation vessel

Executive Summary

The cost analysis in this study provides a high-level estimate of costs that are representative of commercial-scale wind energy projects that could be installed in New York waters of Lakes Erie and Ontario. A range of scenarios were considered, including reference years of 2030 and 2035 and plant capacities between 100 megawatts (MW) and 800 MW. Additional costs for wind energy installations in the Great Lakes relative to Atlantic offshore wind include costs associated with ice protection such as de-icing measures and ice cones on the substructure. For 400-MW wind plants with a Commercial Operations Date (COD) of 2030, levelized cost of energy (LCOE) ranges from $96/MWh to $118/MWh, decreasing to between $89/MWh and $110/MWh for wind plants with a COD of 2035. The range of LCOEs is similar across both Lakes Erie (fixed bottom) and Ontario (floating), however, there were some differences based on the modeled operational and capital expenditures for fixed bottom versus floating substructures. The assumptions made in the cost analysis were generally conservative and rely mostly on existing technologies. Great Lakes wind developers and New York State may find more creative and innovative technology solutions that adapt to the local conditions and reap the associated cost reductions. However, there is substantial uncertainty in capital and operational expenses due to the fact that novel designs may be required for fixed-bottom substructures, and floating wind technologies in general are relatively new. Any actual wind energy development would require detailed, site-specific analysis to assess its technical and economic feasibility.

1 Introduction

This report provides a projection of costs for 2030 and 2035 commercial-scale wind energy development in the New York State waters of Lake Erie and Lake Ontario. The cost analysis uses a regional model developed by National Renewable Energy Laboratory (NREL) to assess costs for offshore wind throughout the United States. Cost assumptions were modified to reflect the unique specifications of potential wind energy projects in the New York State Great Lakes. Key differences between the Great Lakes and ocean settings include the infrastructure of the ports and locks, types of vessels that can access project sites, wave climate, and presence of lake surface ice. The cost model combines information about these site-specific factors with geospatial data across the study area to estimate how costs may vary throughout the region and over time.

As part of a feasibility study, this report provides a high-level estimate of costs that are representative of projects that could be installed in Lake Erie or Lake Ontario. The scope of the report does not include detailed engineering designs of each component, instead it relies on documented industry cost trends and proportionate adjustments to these costs where needed. The unique aspects of the New York State Great Lakes region are considered here but are examined in more detail in several of the accompanying research to this feasibility study. Physical site conditions and geohazards are in New York State Great Lakes Wind Energy Feasibility Study: Evaluation of Site Conditions (NYSERDA 2022a), Physical Siting Analysis (NYSERDA 2022b), and Geophysical and Geohazards Characterization (NYSERDA 2022c), ports and infrastructure in the Feasibility Study's Infrastructure Assessment (NYSERDA 2022d), fixed and floating substructures in the Feasibility Study's Substructure Recommendations (NYSERDA 2022e), and grid interconnection is in the Study's Interconnection Report NYSERDA 2022f). High-level findings that impact costs are summarized briefly in this report; for more in-depth analysis the reader should consult the relevant reports.

2 Methodology

2.1 Analysis Tools

The cost analysis was carried out with NREL's Offshore Regional Cost Analyzer (ORCA), which evaluates the levelized cost of energy (LCOE) within a wind resource area and projects future costs based on innovation trajectories (Beiter et al. 2016). ORCA uses geospatial information to provide site-specific cost estimates that represent the effects of physical parameters such as average wind speed, wave height, water depth, and distances to land-based infrastructure.

The LCOE is derived from a bottom-up assessment of cost inputs in ORCA. LCOE represents the total average cost of building and operating an offshore wind plant per unit of generated electricity over the lifetime of the plant. The four cost components used to calculate LCOE are capital expenditures (CapEx), operational expenditures (OpEx), annual energy production (AEP), and financing terms represented by a fixed charge rate (FCR). CapEx represents the capital costs per kilowatt required to reach commercial operation of the plant including procuring materials and equipment, installation, project development, and "soft" costs such as development, insurance, construction financing, and contingencies. OpEx includes the cost of labor, facilities, equipment, and materials for day-to-day operations as well as maintenance and repairs over the lifetime of the plant, expressed in terms of an annual average per kilowatt. AEP represents the average annual energy production of the plant over the plant's lifetime. ORCA's assessment of AEP depends primarily on site-specific wind speeds at the turbine hub height, the turbine power curve, and losses including transmission losses, maintenance downtime, wake losses, and other factors detailed by Beiter et. al (2020). The FCR is akin to a discount rate defined as the annual revenue required per dollar of investment to pay taxes and carrying charges on the investment. ORCA uses the following equation (Beiter et al. 2016) to calculate LCOE from these inputs:

$$\boldsymbol{LCOE = \frac{FCR \times CapEx + OpEx}{AEP}}$$

2.2 Scenario Development for Great Lakes Wind Energy Cost Modeling

We developed scenarios for cost analysis incorporating regional factors that distinguish the Great Lakes from other offshore wind sites. To provide detailed cost estimates, ORCA requires specific wind plant parameters such as turbine capacity and layout. Our scenarios aim to be representative of the general characteristics of potential wind power plants in the Great Lakes; however, the design of any future wind energy projects may differ from the parameters modeled in this study based on local site conditions and technology selection. The parameters chosen for modeling on each lake are summarized in Table 1 and described in depth in the following subsections.

Table 1. Summary of Cost Modeling Scenario Parameters

Parameter	Lake Erie Scenarios	Lake Ontario Scenarios
Plant Capacity	100 / 400 MW	400 / 800 MW
Turbine Rated Power	6 MW	6 MW
Commercial Operation Dates	2030, 2035	2030, 2035
Substructure Technology	Fixed bottom	Floating
Plant Locations	Area within State waters farther than 4 miles from shore	Area within State waters farther than 4 miles from shore
Wind Turbine Array Layout	7D × 7D[a] spacing on square grid	7D × 7D spacing on square grid

[a] D = turbine rotor diameter

2.2.1 Plant Capacity

The total capacity of a wind power plant is an important parameter selected during the development of a project that depends on several site-specific factors including the area available for development, the amount of transmission interconnection capacity, and installation logistics. This study focuses on modeling commercial-scale offshore wind costs, rather than pilot-scale projects. Smaller demonstration projects provide opportunities to develop and prove technologies before deploying them at scale; however, the per-kilowatt costs of such projects are typically high relative to commercial projects. Larger plants have higher total costs, but typically benefit from economies of scale that enable lower costs per kilowatt. In most offshore lease areas on the Atlantic, project sizes are approaching 1,000 MW for this reason. However, for this cost analysis we chose a constant plant capacity of 400 MW. This plant size allows for cost comparisons between both lakes based on a common baseline plant capacity. The 400 MW plant size represents a plausible size for a small commercial-scale project that is compatible with the estimated currently available headroom for new generation capacity at potential points of connection to the electric grid in Upstate New York and accounts for the limited developable area in Lake Erie. We consider two additional scenarios that illustrate how cost varies with plant size: a capacity of 100 MW in Lake Erie that is representative of a pilot scale project, and a larger capacity of 800 MW in Lake Ontario.

2.2.2 Turbine Selection and Installation

The locks on the St. Lawrence Seaway limit the maximum breadth (width) of a vessel passing through to 23.7 m (Great Lakes St. Lawrence Seaway Development Corporation n.d.). Since the ocean-based wind turbine installation vessels capable of installing 12+ MW turbines are too wide to enter the Great Lakes, we only consider turbines which can be installed by modular, expandable barges with crawler cranes that can be assembled in situ. This strategy is similar to that used to install turbines on fixed-bottom foundations at Windpark Fryslân in the Netherlands (Port of Amsterdam 2021; Windpark Fryslân 2021). We evaluate costs for a turbine rating of 6 MW, which is comparable to offshore wind turbines installed globally between 2017 and 2019. Although offshore wind turbine capacities are growing well beyond 6 MW, we believe that the Great Lakes will be able to leverage local supply chains that already manufacture many components for America's land-based wind industry (Wiser, Bolinger, et al. 2021). Wind turbine manufacturers are beginning to offer land-based turbines rated at 6 MW and this land-based market may be more sustainable than the declining market for 6-MW offshore wind turbines. As a point of reference, NREL's Annual Technology Baseline expects the average rating of land-based wind turbines installed in the United States in 2030 to be between 4–7 MW (NREL 2021). Turbines of this size are therefore likely to be readily available and in the near-term, may be more appropriate to the scale of infrastructure on the Great Lakes than the 15-MW wind turbine platform the industry is adopting for the offshore market. Although this analysis is based on the 6-MW land-based platform, it does not preclude the possibility that Great Lakes wind infrastructure could be adapted for larger turbines, especially on Lake Ontario.

2.2.3 Commercial Operation Dates

We model commercial operation dates (CODs) of 2030 and 2035. This represents the year in which the wind plant begins operation and the starting point of the assumed project life (25 years in this case). Providing cost estimates in multiple years allows us to examine how costs change over time. New York

State's Climate Leadership and Community Protection Act (Climate Act) requires the State to reduce economy-wide greenhouse gas emissions 40% by 2030, including a target of 70% renewable energy generation. The Climate Act also mandates a goal of a zero-emission electricity sector by 2040. Wind plants that began operations in 2030 or 2035 could potentially contribute to meeting this electricity sector target.

2.2.4 Substructure Technology

Fixed-bottom substructure technologies are commercially viable for water depths of up to around 60 m, after which floating substructure technologies are preferred (Walt Musial, Spitsen, et al. 2021). All of New York State's Lake Erie waters are shallower than 60 m, so we evaluate costs assuming fixed-bottom substructures exclusively. In Lake Ontario, only 7% of State waters beyond 4 miles from shore (and less than 0.1% beyond 10 miles from shore) are shallower than 60 m, so our cost analysis assumes floating substructures exclusively.

Substructure costs in the Great Lakes are likely to be incrementally higher than offshore wind substructure costs in the Atlantic because their design must incorporate the impacts of freshwater ice formation and the wind turbine technology is size limited by constraints on transportation and installation logistics. Several potential substructure configurations were identified in the New York State Great Lakes Wind Energy Feasibility Study: Substructure Recommendations report NYSERDA 2022e). Costs for offshore support structures depend on several factors:

- Material inputs: the amount of steel or concrete required and the cost of these materials.
- Geospatial variables—in particular, the water depth is a key determinant of material requirements for fixed-bottom substructures, and the wave climate affects the loading on the substructure.
- Turbine size: this includes the weight of the turbine that the substructure needs to support, the magnitude of the forces that the substructure must withstand (thrust and moment arm).
- Labor: the amount of labor hours varies depending on the complexity of the substructure assembly and installation processes.
- Engineering and design: required for all projects, more expensive for an untried substructure concept or complex site conditions.
- Installation: the distance to port affects the amount of time and labor required for installation, and the vessels required for installation vary by substructure type. Port and vessel costs are discussed in section 2.2.8.
- Ice protection: designing, acquiring materials for, and building the ice cone adds extra cost substructures for wind turbines in the Great Lakes.

NREL has validated existing cost modeling tools for monopiles and semisubmersible substructures that incorporate the material costs, labor, design, depth scaling, wind and wave impacts, vessel costs, and turbine scaling effects on substructure cost. Although these substructure designs are not considered feasible in this region, the cost drivers are the same for the substructures that are considered. In Lake Erie, we assume that costs for a monobucket foundation will scale similarly to costs for a monopile across the relevant range of depths and shore distances. In Lake Ontario, a hybrid substructure design is estimated to have similar material and installation costs as a semisubmersible design. For both lakes, we additionally consider the cost of design adaptations for surface ice (Table 6).

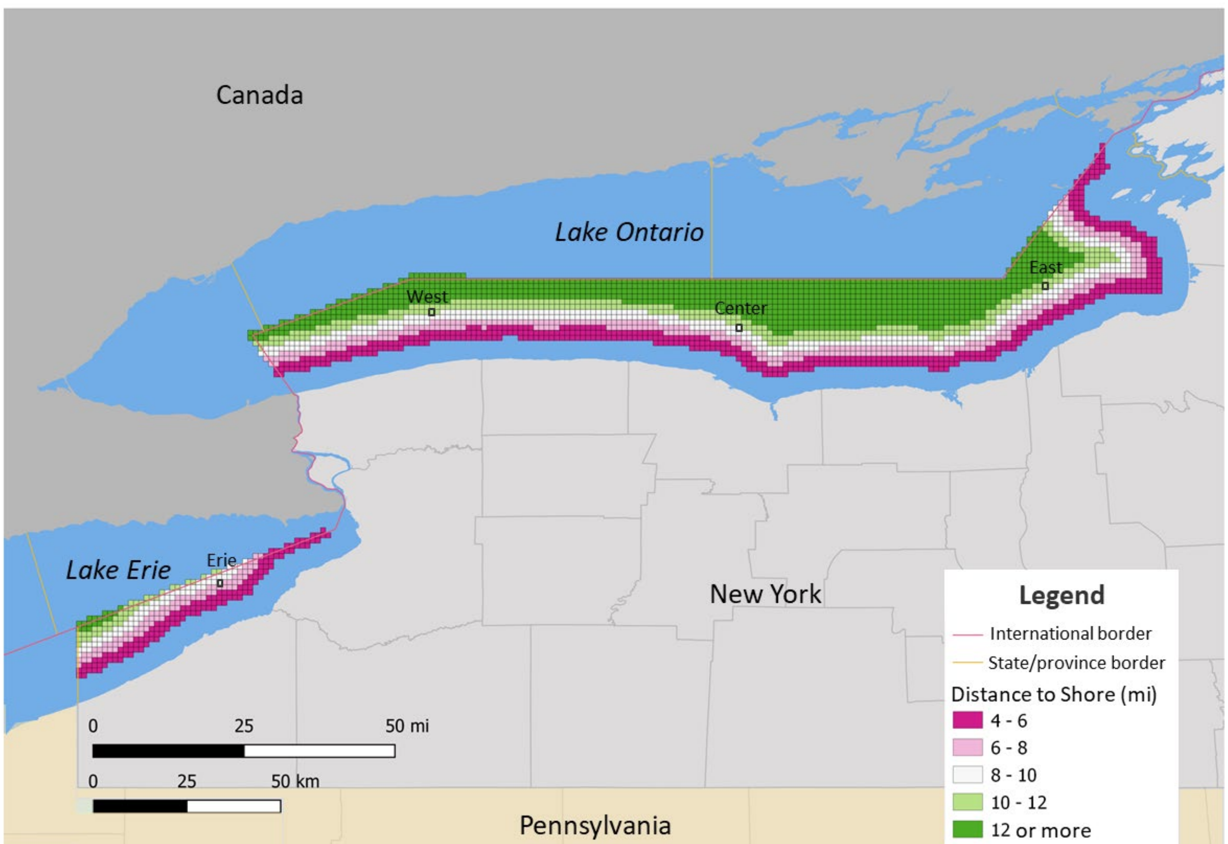
2.2.5 Plant Locations

We provide cost estimates for hypothetical plant locations at equally spaced grid points across each lake, within the boundary of New York State waters and utilizing a minimum distance to shore. The analysis grid consists of rectangles that are one minute in latitude by one minute in longitude, approximately one square mile or 2.5 km.[2] For more detail regarding the analysis grid, see the New York State Great Lakes Wind Energy Feasibility Study: Geophysical and Geohazards Characterization report NYSERDA 2022c). We do not assess costs for potential wind energy development within 4 miles of the shoreline, because average wind speeds are lower close to shore, the initial assessment of environmental and visual impacts suggests a greater potential for conflict in these areas, and the potential for ice build-up is greater. The results are presented in the form of geo-spatial heat maps that can provide insight into how the levelized cost of energy varies spatially, without prescribing individual sites for wind energy development (see section 3.0). To provide detailed cost breakdowns and illustrate spatial variation in costs, we chose four hypothetical example locations: a site located 9 miles off the shore in New York State's Lake Erie waters and three sites between 10 and 11 miles from the shoreline of Lake Ontario, spaced equidistantly east-to-west. Physical parameters of the example locations are provided in Table 2.

Table 2. Physical Characteristics of Example Locations Used for Cost Component Breakdowns

Example Locations	Erie	Ontario West	Ontario Center	Ontario East
Distance from shore	9 miles (14 km)	11 miles (17 km)	10 miles (17 km)	11 miles (18 km)
Mean wind speed at 100 m	20 mph (8.8 m/s)	19 mph (8.7 m/s)	20 mph (8.9 m/s)	20 mph (8.8 m/s)
Water depth	78 ft (24 m)	533 ft (162 m)	513 ft (156 m)	615 ft (187 m)
Nearest port	Buffalo	Rochester	Rochester	Oswego
Distance to nearest port	26 miles (42 km)	57 miles (92 km)	16 miles (26 km)	11 miles (18 km)
Nearest point of interconnection	Silver Creek	Somerset	Station 7 (Russell)	Oswego
Distance to nearest grid connection	11 miles (18 km)	11 miles (18 km)	14 miles (23 km)	12 miles (19 km)

Figure 1. Locations of Example Sites for Cost-Component Breakdowns



2.2.6 Wind Turbine Array Layout

We assume a wind plant layout with 6-MW turbines on a square grid spaced 7 rotor diameters apart, consistent with recent NREL cost analyses (Shields, Duffy, et al. 2021; Musial, Duffy, et al. 2021; Beiter et al. 2020). For a 6-MW GE Cypress turbine with a rotor diameter of about 160 meters, the turbine spacing was 1,120 meters. Full layout optimization for detailed site conditions is beyond the scope of this initial cost and feasibility study, but this generic layout geometry helps illustrate representative cost variations across the entire region. This layout spacing is likely to be conservative in terms of wake losses because more optimal layouts that could reduce wake losses would likely be possible. Similarly, viewshed mitigation may also be sub-optimal as certain variables such as array shape, turbine size, and distance from shore have not been adjusted to minimize impacts.

2.2.7 Grid Connection and Electrical System

Cost estimates for grid connection include procurement and installation costs for array cables (66 kV), an offshore substation, one or more export cables (220 kV HVAC, number depending on the plant capacity), cable landfall, and an onshore spur line from the point of cable landfall to the point of interconnection. The New York State Great Lakes Wind Energy Feasibility Study: Interconnection (NYSERDA 2022f) identifies land-based substations with available headroom for interconnection. On Lake Erie, there are renewable energy projects already in the interconnection queue which will compete for the remaining available headroom. For this analysis, we present cost estimates based on substations that are close to the shoreline and have enough capacity to ingest the power today. We do not include estimates of the cost of future bulk power system upgrades. For each modeled plant location, interconnection is assumed to occur at the closest substation. We capture the costs of the array cable collection system, offshore substation, export cable, onshore substation, and a spur line to the point of interconnection. Modeled costs to install land-based transmission lines are aligned with typical costs in New York State.

2.2.8 Port and Vessel Infrastructure and Logistics

The cost of developing wind energy in the Great Lakes will be influenced by the need for port upgrades and the unique accessibility challenges for vessels onto the Lakes. As described in New York State Great Lakes Wind Energy Feasibility Study: Infrastructure Assessment (NYSERDA 2022e), installation vessel options are constrained by the channel width of the St. Lawrence Seaway and the Jones Act, and port options are limited by channel widths, channel drafts and quayside space. These challenges are accounted for in the cost estimates.

Locks on the St. Lawrence Seaway have a minimum width of 24.4 m, limiting vessels on the Seaway to a maximum width of 23.7 m. This eliminates all existing wind turbine installation vessels (WTIVs) and heavy lift vessels for the 6-MW turbine class. In addition to the limits of the St. Lawrence Seaway, the Jones Act stipulates that any vessel transporting goods between two U.S. ports must be built, registered, owned, and operated by U.S. citizens. This further restricts the use of existing Canadian vessels.

In modeling the cost of Great Lakes wind plants on Lake Erie, we assume that turbines and substructures will be installed using custom vessels created by combining multiple barges that can be brought through the locks or that are stationed on the Lakes. The multi-barge installation vessel would be Jones Act compliant, addressing both primary limitations introduced above. The day rate for a custom installation vessel is assumed to be higher than the combined day rate of existing barges to cover the cost of its assembly. The day rates for tugs used to tow floating wind turbines to sites on Lake Ontario are assumed to be the same as conventional ocean-going tugs. In the Atlantic and North Sea, offshore wind installation activities are typically concentrated in the summer months. Wind energy projects in the Great Lakes would also be likely to adopt a summer construction season, which avoids high waves during autumn storms and ice cover in the winter and early spring.

We assume that installation vessels are based out of the nearest port among the following options: Oswego, Rochester, and Buffalo, NY, and Erie, PA. Each of these ports would likely need to upgrade their existing infrastructure to accommodate wind plant components, such as widening and or deepening navigation channels and berths or expanding quayside space for component staging, but all have been vetted for fatal flaws such as low air draft (overhead clearance). The cost to rent port space for supporting construction and operation of wind farms on the Great Lakes may increase to reflect these upgrades. Port fees are incorporated into the project CapEx in the "Port, staging, logistics, and fixed cost" line item. The cost of port upgrades does not contribute directly to the LCOE as they are typically borne by other parties such as the port operator, State and federal agencies, and other users of the port; however, fees for use of the port may increase to recoup the upgrade investments. As with vessels, the level of additional costs depends on the assumed regional buildout, and the strategy for deployment and co-locating supporting manufacturing and assembly facilities. If a port can support multiple projects, the incremental increase in port fees during construction and operation can be reduced. To illustrate how port costs might be spread across various levels of wind energy deployment, we consider the example of New London, CT, which is upgrading its facilities to support offshore wind for an estimated cost of $157 million (Ørsted n.d.).If a developer were to make a comparable investment in the Great Lakes for a single 400-MW wind plant, it would add nearly 10% to the total CapEx, increasing LCOE by $10-$12/MWh in 2030. If that same investment were able to support projects totaling 6 GW, the increase in CapEx would be less than 1%.

2.2.9 Annual Energy Production and Loss Estimates

Annual energy production (AEP) is one of the factors with the largest impact on LCOE. Using the most recent wind resource data available, NREL has estimated AEP for wind farms in Lakes Erie and Ontario with its ORCA and FLOw Redirection and Induction in Steady State (FLORIS) models (Beiter et al. 2016; National Renewable Energy Laboratory [NREL] 2019). The turbine power curve used for the energy yield assessment was taken from Musial et al. (2016) (tabular data available on GitHub[1]).
As discussed in New York State Great Lakes Wind Energy Feasibility Study: Evaluation of Site Conditions (NYSERDA 2022a), a new wind resource data set was generated with the Weather Research and Forecasting model utilizing the methodology of Optis et al. (2020) and represents the most up-to-date wind resource assessment for the Great Lakes. The data set covers the period 2000 through 2020, and the wind resource was taken at a height of 112 meters (m). Loss categories considered in the AEP calculation process are listed in Table 3 along with the values or ranges used in this study. Loss differences between fixed-bottom and floating turbines are assumed to be minimal, with only 0.2% of additional technical losses assumed for floating compared to fixed-bottom (for differences in onboard equipment and rotor misalignment).

Total AEP improvements of 7% and 11% by 2035 (for fixed and floating, respectively) are included to capture the effects of technology maturity over time on the turbine and wind plant performance based on Wiser, Rand, et. al (2021).

1 Power curve data available on GitHub.

Table 3. Losses Used in AEP Calculation

Loss Category	Value (% of Gross Energy Production)	Additional Information
Wake losses	6.9-8.0%	Evaluated using FLORIS for 100-, 400-, and 800-MW wind plants made up of 6-MW turbines at 7D × 7D spacing.
Environmental losses	3.0%	Includes icing, temperature-related shutdowns, and lightning.
Technical losses	1.0-1.2%	Includes power curve hysteresis, onboard equipment power usage, and rotor misalignment
Electrical losses	2.5-3.5%	Losses in transmission system, varies with distance to POI.
Availability losses	6%	Losses during periods when system is unavailable, e.g., maintenance and repair of turbines or balance of system components.

2.2.10 Ice and Cold Weather Protection

Low temperatures and icing can impact the ability of turbines to operate (Bredesen et al. 2017). In cold climates, ice accumulation on wind turbines can reduce energy production by degrading aerodynamic performance and by creating conditions that require turbines to shut down such as heavy or asymmetric ice loading and ice throw risks. Thorough site assessment is needed to properly characterize the energy production impacts of icing in specific locations. Estimates of icing frequency in the Great Lakes region in New York State fall into IEA Ice Class 1 or 2, which suggests that AEP losses may increase by up to 5% for turbines without blade de-icing capabilities (Bredesen et al. 2017; Rissanen and Lehtomaki 2016). In the Great Lakes, wind energy developers also need to consider ice formation on the lake surface. The effects of surface ice are primarily relevant to the substructure design and maintenance access to wind turbines during the winter months. The meteorological conditions for lake surface ice formation are not identical to those that produce blade icing. Although both require freezing temperatures, lake surface ice formation depends on low-water temperatures, which differs between lakes due to their varying depths, whereas blade icing requires water droplets to be present in the air. Lake surface ice can be characterized by the total accumulated area covered by ice, which has a median value of 27% in Lake Erie and 6% in Lake Ontario (U.S. National Ice Center 2021). Because total accumulated cover is calculated only from December to June, these values correspond to annual averages of 14% and 3% ice cover, respectively.

Cold climate or cold weather turbine packages are available to improve turbine performance and availability for additional cost. These packages typically include the following modifications (depending on the manufacturer):

- Materials suited for low temperatures (alloys and elastomers in lieu of rubbers).
- Welds performed with low temperature flux.
- Low temperature lubricants (grease, oils, hydraulic fluids) and/or heating systems for lubricants in generator, gearbox, yaw and pitch systems, converters, and transformers.
- Robust sensors with an extended range of operational temperatures or heated sensors to prevent ice formation.
- Control system designed for cold temperature turbine operation.
- Heated and sealed nacelles.
- Ice detection systems that enhance safety and protect turbine components by identifying uneven loading or ice throw risks.

Anti-icing coatings or de-icing systems (thermal, electrical, mechanical) are also available, but tend to come at a cost premium over the basic cold weather turbine operation packages, so need to be justified by sufficiently increasing energy output or providing other benefits. The cost and performance of these systems vary and the presence of an anti-icing system does not guarantee availability under all circumstances (Fakorede et al. 2016). Detailed measurements would be needed to determine if the added availability/value from anti-icing or de-icing systems would outweigh the additional cost. In this analysis, NREL makes the conservative assumption that a cold weather package with de-icing capabilities is included on wind turbines for Great Lakes. NREL captures these added costs with a 10% increase in the turbine CapEx line item (turbine CapEx represents approximately 28–37% of total CapEx across the domain for 400 MW plants). In addition, we assume a 1.4% loss increase in environmental losses due to icing and blade soiling (Table 6).

Wind turbine substructures can be protected against lake surface ice using an ice cone, as described in section 2.2.4. The cost of operations and maintenance (O&M) will also be impacted by ice conditions. Although de-icing systems reduce the direct impact of ice on turbine performance, ice cover on the lake surface also affects the ability of vessels to operate on the lakes and access wind turbines if maintenance is needed. Reduced accessibility during the winter months could lead to lower availability, which we represent with a 1% increase in availability losses over standard baseline assumptions (Table 6). There are also opportunities to increase access using higher-cost O&M solutions (e.g., icebreakers, helicopters). A detailed assessment of the relative costs and benefits of winter maintenance access was outside the scope of this study. Therefore, we assume there will be an incremental increase of 15% in O&M costs relative to a similar ocean-based offshore wind plant (Table 6).

2.2.11 Offshore Wind Energy Project Financing

For analyzing offshore wind energy projects in the Great Lakes, we aligned financing terms with Stehly and Duffy (2022), which reflects recent industry trends in fixed-bottom project financing. As in Beiter et al. (2020), we assume floating offshore wind projects benefit from identical financing terms as commercial-scale fixed-bottom projects. While this is likely nonconservative in the short term given the nascent state of the floating offshore wind industry, Weber (2020) suggests that in the long run floating projects will benefit from similar financing terms because of the following similarities:

- Project developer experience
- Mature supply chains
- Low-political risk
- Technology maturity
- Limited-to-no revenue risk
- Insurance coverage
- Contract management practices
- Contingency budgets

If there is a longer development timeline for floating projects on the Great Lakes than assumed in this report (e.g., 2030), the financing terms could differ from fixed-bottom projects. A summary of the financial assumptions is provided in Table 3. The baseline financing assumptions do not include tax credits or subsidies. Note all costs presented in this report are in nominal 2021 U.S. Dollars, unless otherwise specified. This means effects from inflation are excluded from the COD year throughout the operational lifetime of the project. No assumption is made about the inflation rate between 2021 and the COD year.

Table 4. Project Financing Parameters (Nominal and Real)

Financing Parameters	Nominal	Real
Project design life	25 years	25 years
Combined state and federal tax rate	26%	26%
Inflation rate	2.5% (not included)	2.5%
Weighted average cost of capital (after-tax)	5.29%	2.72%
Capital recovery factor (after-tax)	7.3%	5.6%
Depreciable basis	100%	100%
Depreciation schedule	5-year MACRS	5-year MACRS
Depreciation adjustment	87%	87%
Project finance factor	105%	105%
Fixed charge rate	7.64%	5.82%

2.2.12 Cost-Projection Methodology

This study employs the learning-curve based cost projection methodology developed in Beiter et al. (2020) to estimate future floating offshore wind costs in California. Future fixed-bottom and floating costs are obtained by applying cost reductions derived from supply chain learning, technological innovations, and economies of plant size to the baseline costs obtained with NREL's ORCA and Offshore Renewables Balance-of-system Installation Tool (ORBIT) bottom-up cost models. Cost reductions associated with turbine and plant scaling are captured with ORBIT and used to inform plant scaling relationships (Shields, Beiter, et al. 2021).

Learning and experience curves represent the decrease in input costs as an increasing number of units of a good or service are produced (Louwen and Subtil Lacerda 2019). An offshore wind industry learning rate describes the percentage cost reduction for each doubling of cumulative installed offshore wind capacity. Louwen, Junginger, and Krishnan 2018) attribute these cost reductions to:

- Learning by doing
- Learning by researching
- Improved supply chain and manufacturing efficiencies
- Investment

We utilize NREL's Forecasting Offshore wind Reductions in Cost of Energy (FORCE) [2] model (Shields, Beiter, and Nunemaker forthcoming) to obtain the learning rate in terms of percent CapEx reduction per doubling of installed capacity worldwide—derived from a multivariate linear regression of historical global offshore wind CapEx data going back to 2014. Since limited cost data are available for the few existing pilot-scale floating offshore wind projects, commercial scale fixed-bottom cost data are analyzed to obtain the experience factor for floating offshore wind. The linear regression process controls for turbine rating, plant capacity, water depth, distance to shore, and installation country to remove their effects from the learning rate since the cost impacts of these are accounted for in the bottom-up cost modeling.

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[2] Available on GitHub: https://github.com/JakeNunemaker/FORCE

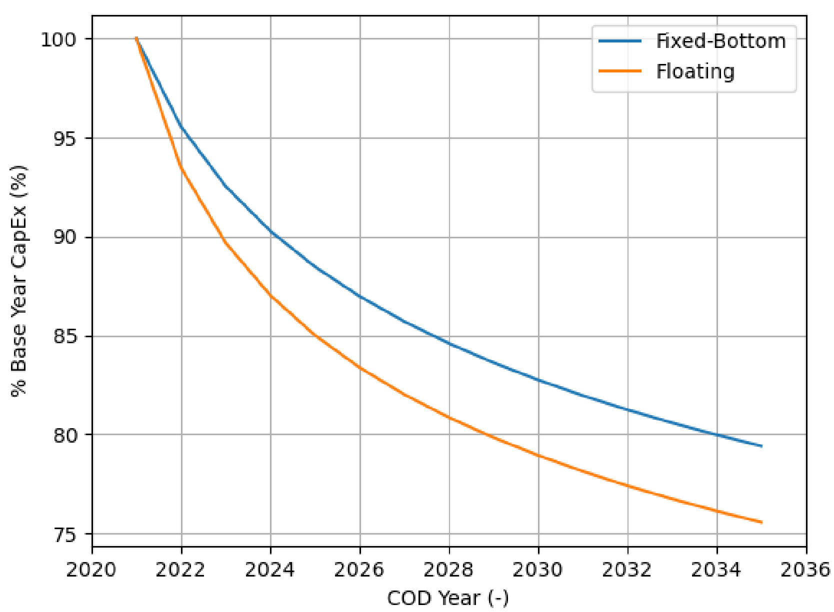
This learning rate is then translated into a learning curve (and cost reductions) based on projected global fixed-bottom and floating offshore wind deployment in a future year. Based on estimates derived from literature forecasts, we assume nominal values for global offshore wind deployment levels in 2030 and 2035 for fixed-bottom and floating turbines, respectively.

Table 5. Offshore Wind Capacity and CapEx Learning Rates Derived from Market Data

Year	Data Source(s)	Global Fixed-bottom Wind Capacity	Global Floating Wind Capacity
2020	Musial, Spitsen, et al. (2021)	32.9 GW	0.08 GW
2030	GWEC, 4C Offshore, Wood Mackenzie, Strathclyde, Equinor	229 GW	9.7 GW
2035	ORE Catapult	277 GW	14.4 GW
CapEx Learning Rate	**FORCE Model (Shields, Beiter, and Nunemaker forthcoming)**	**7.3%**	**7.3%**

The resulting fixed-bottom and floating offshore wind CapEx reductions from learning are presented in Figure 2 as a percentage of the base year costs obtained with bottom-up modeling. Note that more aggressive reductions are expected for floating offshore wind since it is in an earlier stage of total global deployment, technology is rapidly maturing, and the onset of commercial deployment expected in the next few years will result in several "doublings" of the global floating market.

Figure 2. CapEx Reductions from Learning



Because empirical data for OpEx and AEP are largely unavailable to derive learning curves, we rely on expert elicitation to estimate the impacts from technology improvements. Total OpEx reductions of 22% between 2019 and 2035 for fixed-bottom wind and 12% for floating, and AEP improvements of 7% and 11%, respectively over the same period are based on Wiser, Rand, et. al (2021). Total reductions for each CapEx, OpEx, and AEP input are computed for each future year and applied to the baseline costs before calculating future LCOE.

2.2.13 Summary of Cost Model Customizations for the Great Lakes

Table 6 summarizes the adaptations made to the bottom-up cost modeling efforts to account for the unique characteristics of offshore wind on the Great Lakes. The changes are presented relative to the baseline set of assumptions in ORCA and ORBIT.

Table 6. Summary of Great Lakes-Specific Cost Model Customizations

Category	Description of Changes	Adjustment Relative to Baseline Model
Cold weather and icing	Cold weather package with de-icing capabilities.	+10% Turbine CapEx
OpEx	More costly and reduced winter access for maintenance.	+15% OpEx
Substructure CapEx	Ice cone added to substructure design.	+$56/kW
Port and vessel costs	Increased daily or monthly rates for use of ports and vessels.	+50% PSLT
Environmental losses	Increased blade soiling, and occasional icing or low temperature shutdowns.	+1.4% Environmental Losses
Availability losses	Reduced availability due to lower winter access for maintenance.	+1% Availability Losses

3 Results and Discussion

This section presents the cost results generated with the ORCA cost model using the assumptions and methodology described in previous sections. All costs are for offshore wind power plants with total capacities of 100 MW, 400 MW, or 800 MW and are presented in nominal 2021$. We present cost and wind plant performance results as heat maps depicting the spatial variation throughout the New York State portions of Lakes Erie and Ontario. Heat maps for CapEx, OpEx, and AEP (expressed in terms of net capacity factor, NCF) are presented for wind plants assuming COD in 2030. Modeled costs for wind power plants with COD in 2035 are lower but the geographic distribution of relatively higher and lower costs remains the same as in the 2030 maps.

3.1 CapEx

Spatial variation in costs were calculated for fixed-bottom wind plants in NYS waters of Lake Erie (Figure 2). For wind plants with a COD of 2030, CapEx varies from $3,530/kilowatts (kW) to $4,540/kW with a median value of $3,890/kW. The large range of cost variation reflects a high degree of correlation between several spatial parameters that affect costs: sites in deeper water also tend to be farther from shore, more distant from points of interconnection to the electric grid, and farther from ports for installation, operations, and maintenance. We expect the average CapEx in Lake Erie to decrease by 4.0% between 2030 and 2035. As well, the spatial variation in floating wind plant costs were calculated for NYS waters of Lake Ontario (Figure 3). The range of CapEx in 2030 is between $3,930/kW and $4,340/kW with a median value of $4,140/kW. The largest contributor to the CapEx for floating wind plants in Lake Ontario is the substructure cost, which represents nearly a third of the total. There are opportunities to reduce the cost of individual substructures in the design phase, for example, through standardization of components, minimizing weight, and enabling labor-intensive processes to take place on land rather than on the water when possible. The relative contribution of balance of plant components (including substructures, mooring lines, and array cables) to the total cost per kilowatt can be reduced for larger, higher capacity turbines. We expect the average CapEx in Lake Ontario to decrease by 4.3% between 2030 and 2035. Details of the line items that contribute to CapEx variations between sites are provided in Table 4. Note all values are rounded to the nearest 1% or 1$.

Figure 3. Modeled CapEx per kW in 2030 for a 400-MW Wind Energy Power Plant in New York State Waters of Lake Erie with Fixed-Bottom Foundations

A detailed CapEx breakdown is provided in Table 4 for the highlighted location.

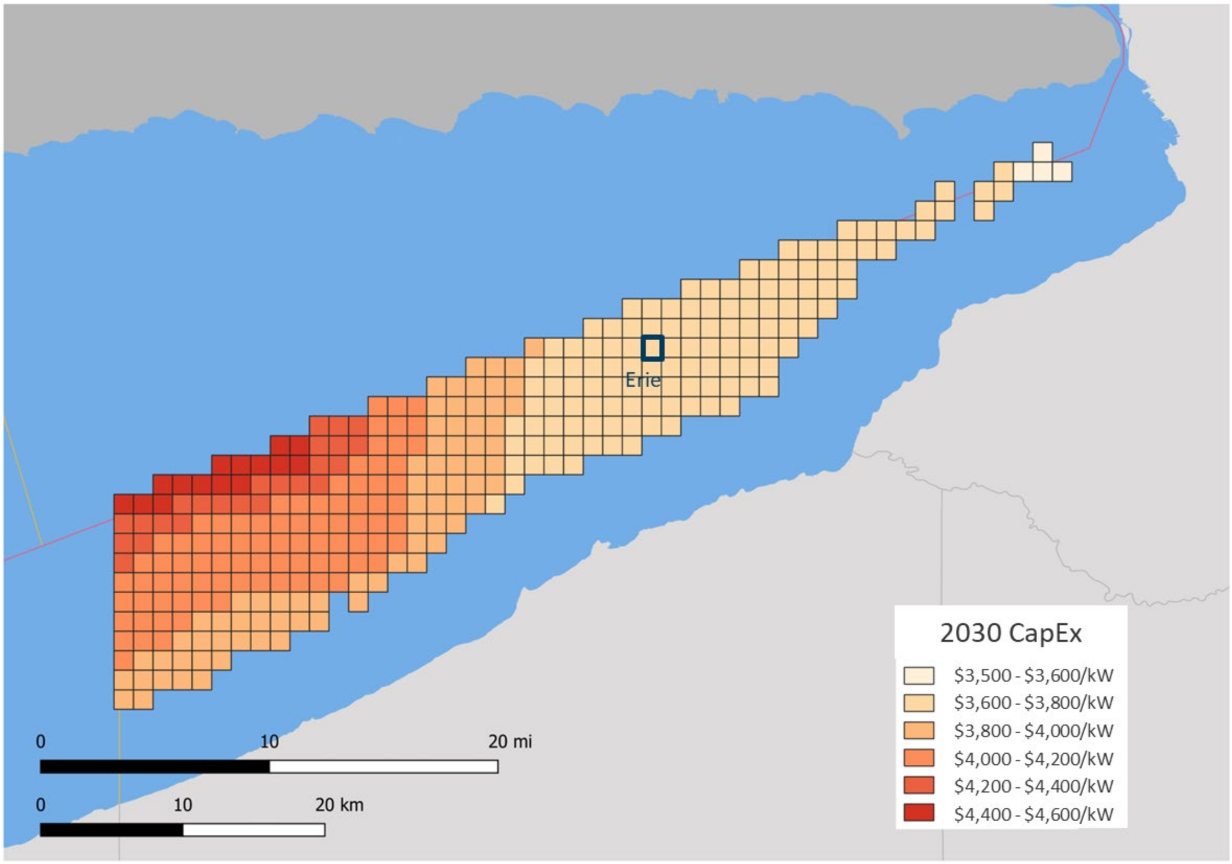


Figure 4. Modeled CapEx per kW in 2030 for a 400-MW Wind Power Plant in New York State Waters of Lake Ontario with Floating Substructures

A detailed CapEx breakdown is provided in Table 4 for the marked locations.

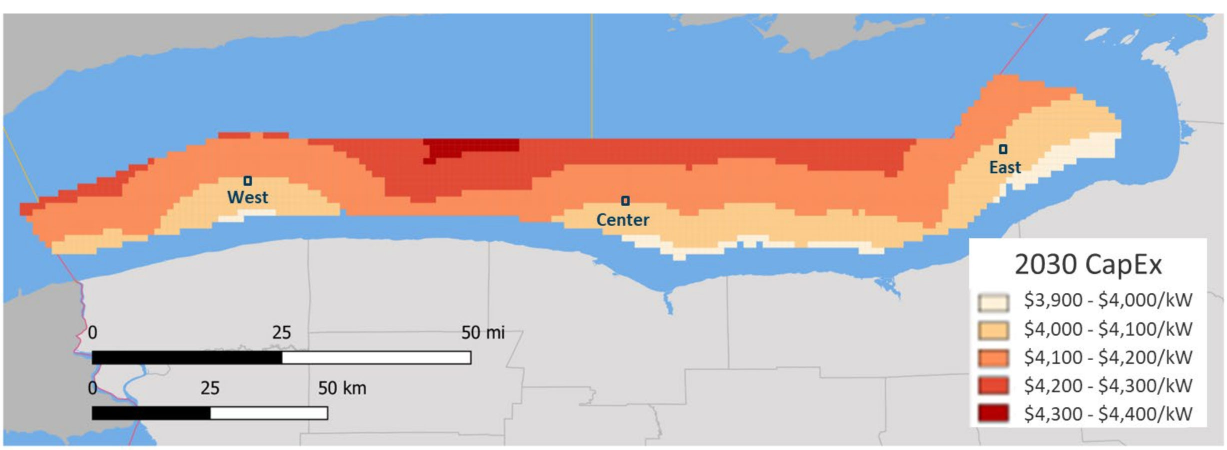


Table 7. CapEx Line Items Expressed as % of Total CapEx for 400 MW Plants

Line Item [values in % of Total CapEx]	Erie	Ontario West	Ontario Center	Ontario East
Tower	5%	4%	4%	4%
Rotor nacelle assembly	30%	26%	25%	26%
Turbine supply	**35%**	**30%**	**29%**	**30%**
Substructure	9%	32%	31%	32%
Foundation (Transition Piece)	7%	N/A	N/A	N/A
Support structure (less tower)	**17%**	**32%**	**32%**	**32%**
Port, staging, logistics, and fixed costs	2%	1%	1%	1%
Turbine installation	3%	2%	2%	2%
Substructure installation	4%	1%	1%	1%
Total installation	**9%**	**4%**	**4%**	**4%**
Array cabling	9%	6%	6%	6%
Export cable and offshore substation	7%	5%	9%	5%
Onshore spur line	1%	1%	1%	1%
Total electric system	**17%**	**12%**	**16%**	**12%**
Development	3%	3%	3%	3%
Lease price	4%	4%	4%	4%
Project management	2%	2%	2%	2%
Balance of system	**51%**	**57%**	**59%**	**57%**
Insurance during construction	1%	1%	1%	1%
Project completion	1%	1%	1%	1%
Decommissioning	1%	1%	*0%	*0%
Procurement contingency	5%	5%	5%	5%
Installation contingency	2%	1%	1%	1%
Construction financing	4%	4%	4%	4%
Total soft CapEx	**14%**	**13%**	**12%**	**12%**
Total CapEx in 2030 [$/kW]	**3727**	**4090**	**4104**	**4078**
Total CapEx in 2035 [$/kW]	**3576**	**3914**	**3929**	**3903**

Note: * indicates value is <0.5%.

3.2 OpEx

Operational expenditures include the ongoing costs of managing operations, carrying out regular maintenance, and repairing or replacing components as needed. A wind plant's proximity to a port that serves as its operations base is the primary geospatial factor affecting OpEx, although factors that affect accessibility such as wave height and ice cover also have an impact. OpEx projections for a 400-MW wind plant were calculated for Lake Erie and Lake Ontario (Figures 4 and 5, respectively). For 400-MW wind plants with a COD of 2030, annual OpEx varies from $73/kW to $91/kW in Lake Erie with a median value of $86/kW. On Lake Ontario, the range of OpEx is between $77/kW and $96/kW with a median of $87/kW. Annual OpEx is modeled to decrease to median values of $79/kW on Lake Erie and $83/kW on Lake Ontario for wind power plants with a COD of 2035.

Figure 5. Modeled Annual OpEx per kW in 2030 for a 400-MW Wind Power Plant in New York State Waters of Lake Erie with Fixed-Bottom Foundations

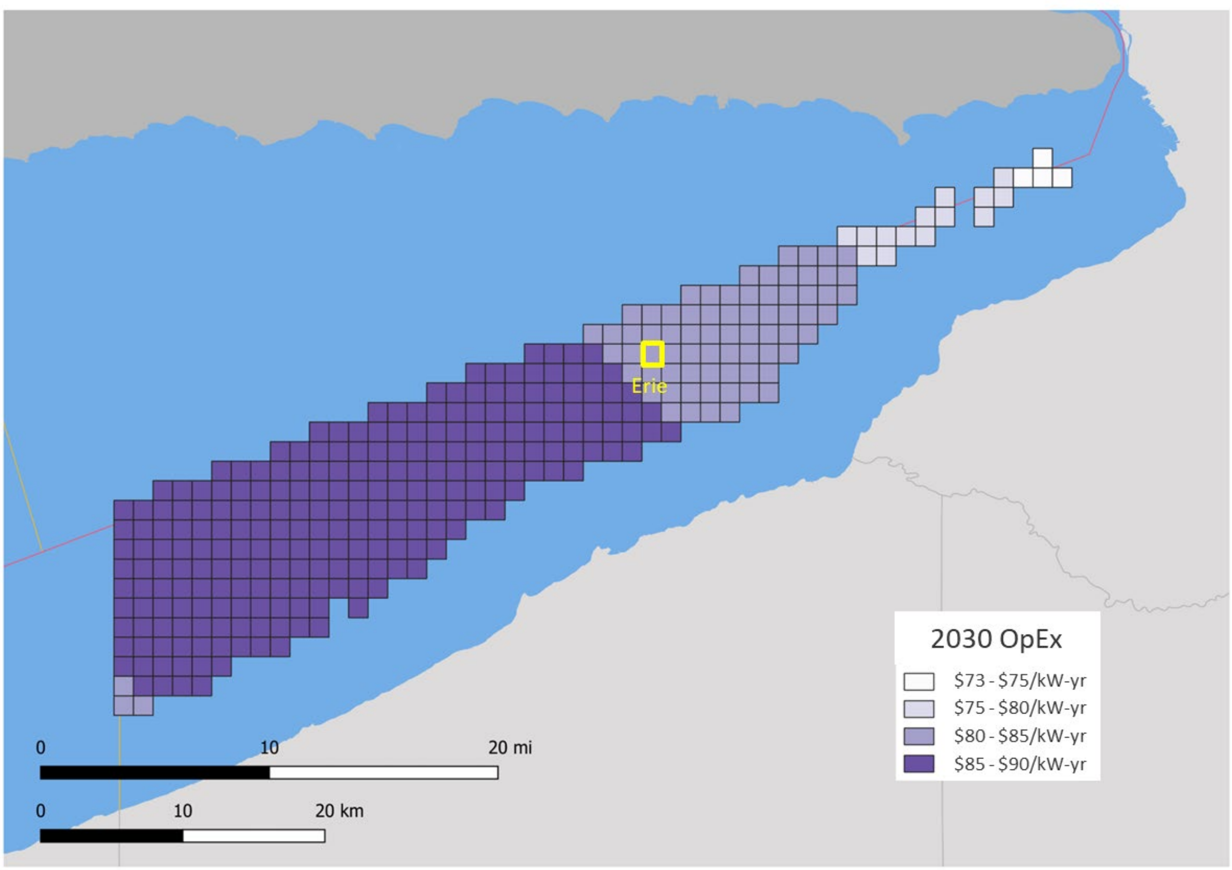


Figure 6. Modeled Annual OpEx per kW in 2030 for a 400-MW Wind Power Plant in New York State Waters of Lake Ontario with Floating Substructures

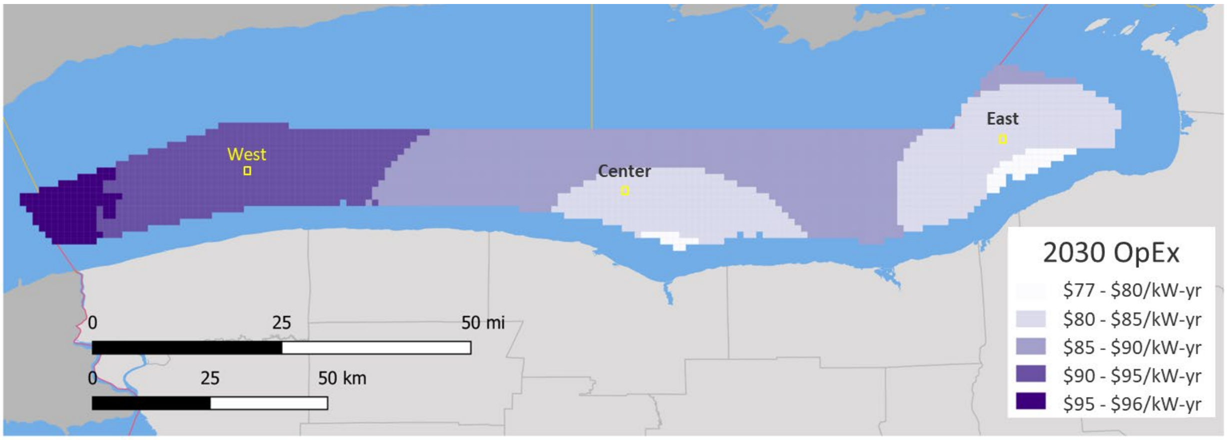


Table 8. Modeled OpEx for 400-MW Wind Power Plants at the Locations Highlighted in Figures 3 and 4

Values expressed as [$/kW-yr]	Erie	Ontario West	Ontario Center	Ontario East
2030 OpEx	85	93	84	82
2035 OpEx	78	89	80	78

Differences between fixed-bottom and floating maintenance costs are driven by O&M strategies analyzed by (Beiter et al. 2016) for mild wave climates similar to those found in the Great Lakes.

3.3 Annual Energy Production (AEP)

AEP has the largest impact on LCOE, but this varies in space with the wind resource. Modeled net capacity factor (NCF) was calculated from AEP normalized by the theoretical maximum annual generation of the plants in Lakes Erie and Ontario (Figures 6 and 7). The minimum NCF on either lake is 41%, with maximum values of 44.0% on Lake Erie and 45.6% on Lake Ontario.

Figure 7. Modeled net Capacity Factor in 2030 of a 400-MW Wind Power Plant in New York State Waters of Lake Erie

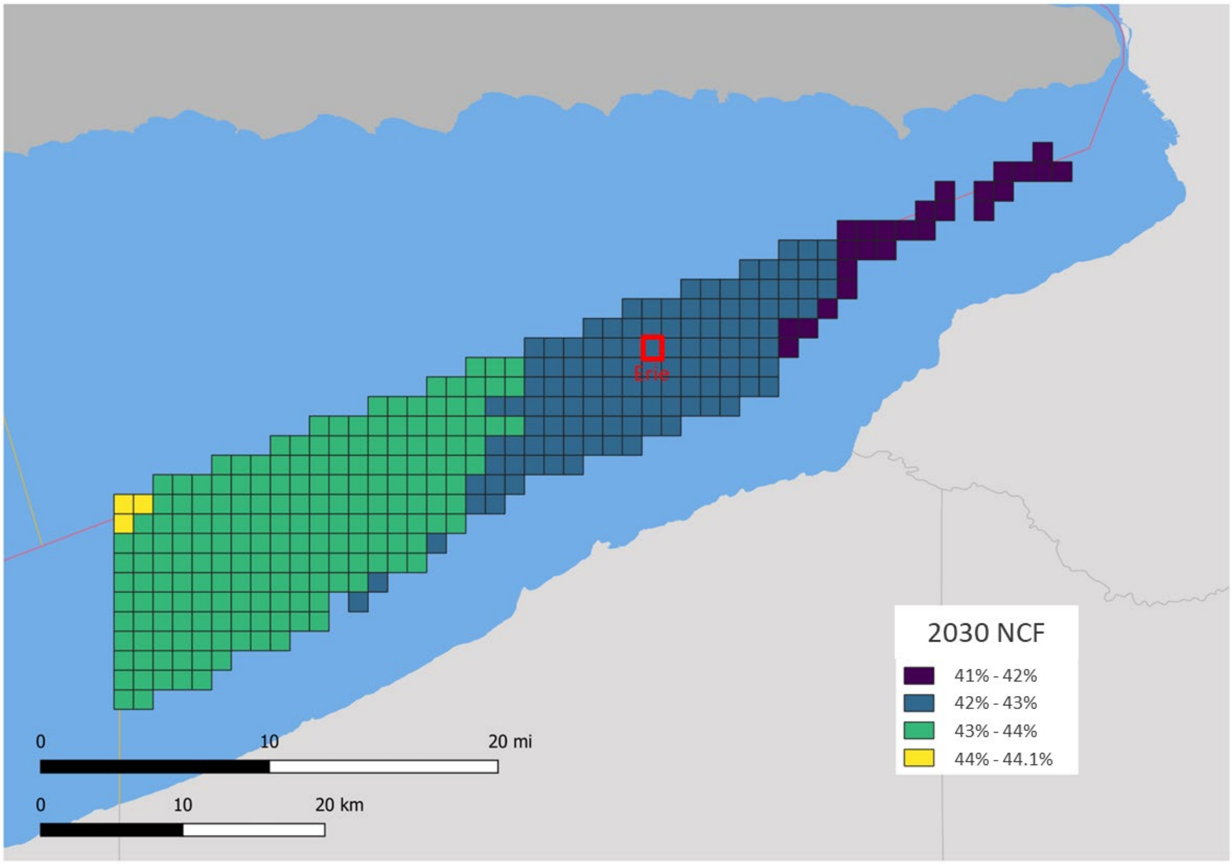


Figure 8. Modeled net Capacity Factor in 2030 of a 400-MW Wind Power Plant in New York State Waters of Lake Ontario

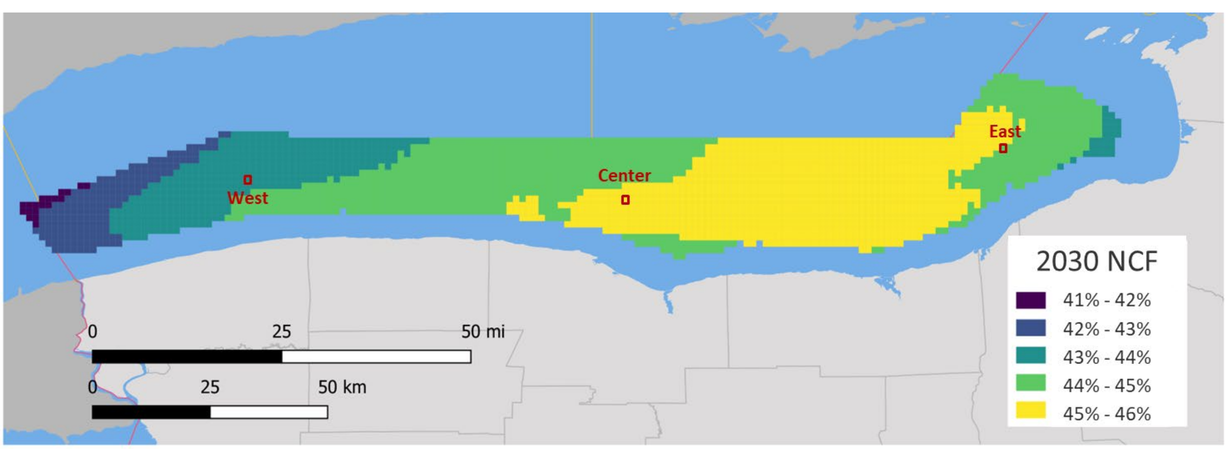


Table 9. Net Capacity Factors

	Erie	Ontario West	Ontario Center	Ontario East
2030 NCF	42.5%	43.6%	45.2%	45.0%
2035 NCF	43.4%	45.0%	46.7%	46.4%

3.4 Levelized Cost of Energy (LCOE)

LCOE values for wind power plants on the Great Lakes incorporate the CapEx, OpEx, and NCF presented in the previous sections. Modeled LCOE for Lakes Erie and Ontario are mapped in Figure 8 and Figure 9, with LCOEs at specific locations provided in Table 7. For wind plants with a COD of 2030, LCOEs range from $96/MWh to $118/MWh with a median value of $105/MWh in Lake Erie and between $97/MWh and $115/MWh with a median value of $103/MWh in Lake Ontario. LCOEs below $100/MWh can be found toward the eastern end of each lake. These areas are close to ports and grid connection opportunities near Buffalo and Oswego and in Lake Erie they tend to coincide with shallower water depths. In both lakes, LCOEs tend to increase as wind power plants are sited toward the western end of the analysis region and farther from shore. By 2035, the median LCOE decreases to $98/MWh in Lake Erie and $96/MWh in Lake Ontario.

Figure 9. Modeled LCOE in 2030 for a 400-MW Wind Power Plant in New York State Waters of Lake Erie with Fixed-Bottom Foundations

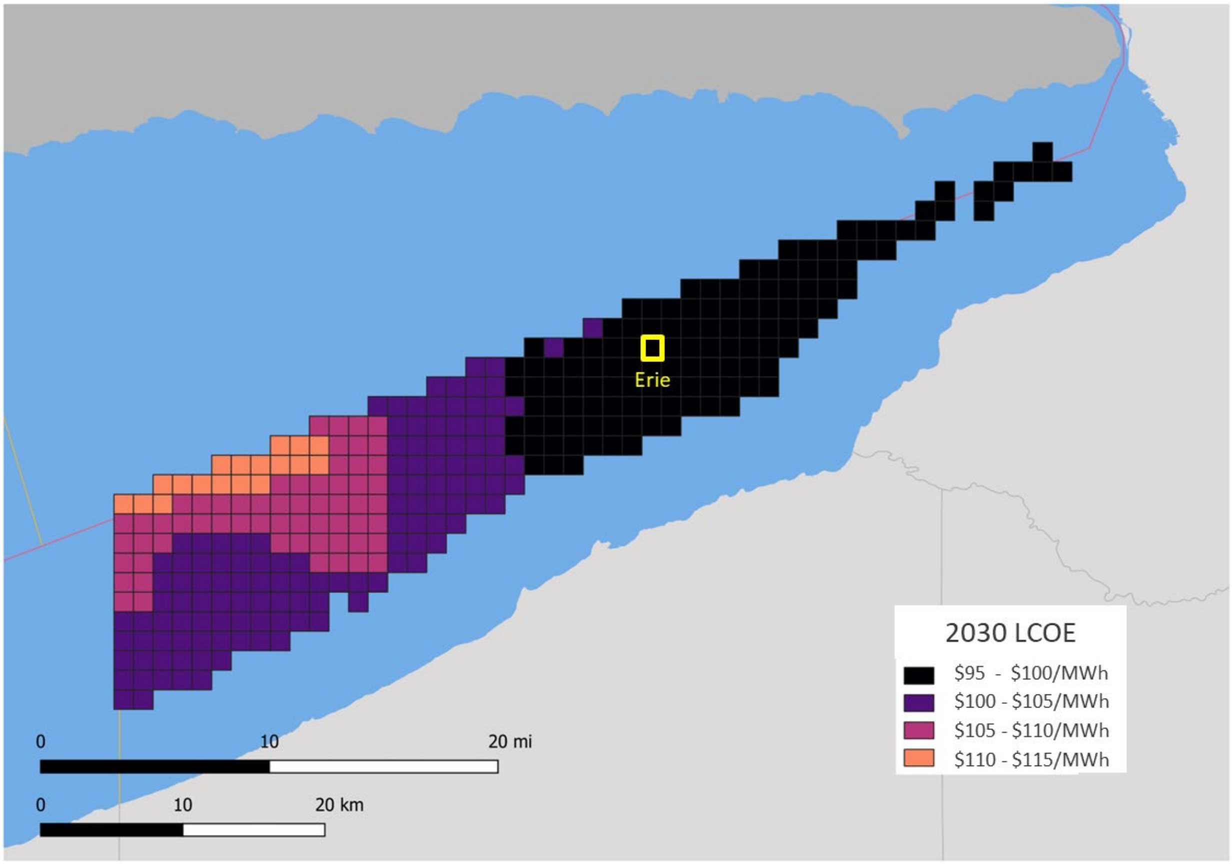


Figure 10. Modeled LCOE in 2030 for a 400-MW Wind Power Plant in New York State Waters of Lake Ontario with Floating Substructures

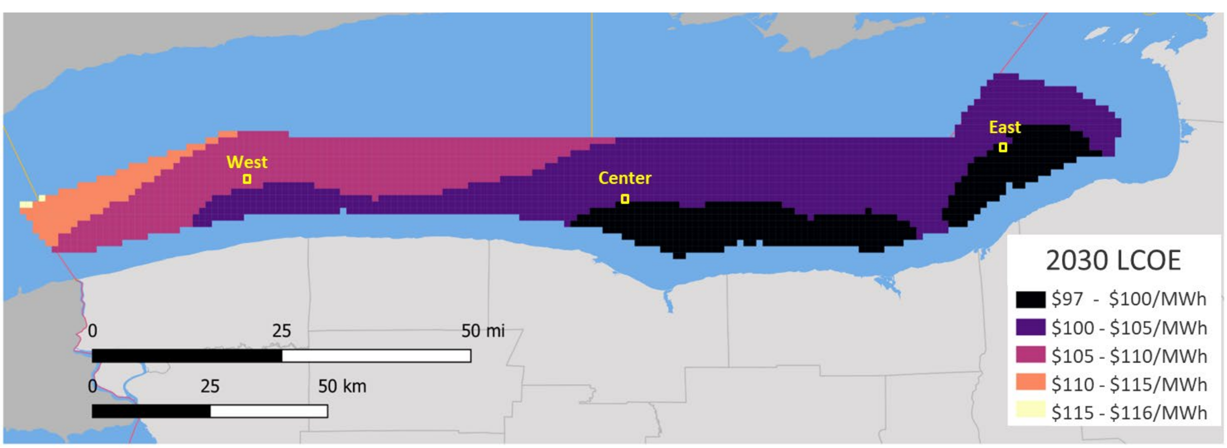


Table 10. Modeled LCOE in 2030 and 2035 for 400-MW Wind Power Plants at Reference Locations Highlighted in Figure 8 and Figure 9

	Erie	Ontario West	Ontario Center	Ontario East
2030 LCOE	$99/MWh	$106/MWh	$100/MWh	$100/MWh
2035 LCOE	$92/MWh	$98/MWh	$93/MWh	$93/MWh

3.5 Impacts from Plant Scale

Economies of plant scale impact offshore wind costs. Costs per kilowatt tend to decrease with increasing plant capacity because fixed costs (e.g., export cables) are amortized over a larger capacity and component pricing improves with larger orders. To illustrate the impact of different plant capacities we considered alternate scenarios of a 100 MW plant in Lake Erie and an 800 MW plant in Lake Ontario. The changes in LCOE are presented in Figure 10, Figure 11 and Table 8. There is a steep increase of between 52% to 56% in cost per megawatt-hour for the smallest plant capacity of 100 MW. The cost decrease in increasing the plant size from 400 MW to 800 MW is about 2% across the study area.

Like with individual plant capacities, the level of capacity installed in a region can affect total costs. If the costs of infrastructure investments such as enhancement of port capabilities and development of specialized vessels are distributed among several projects, they impact individual project LCOEs less than if a single project bears the investment costs. Greater regional buildout of wind capacity can motivate the development of local supply chains that may also benefit from economies of scale.

Figure 11. Change in Modeled LCOE in 2030 for Fixed-Bottom Wind in New York State Waters of Lake Erie as Plant Capacity Decreases from 400 MW to 100 MW

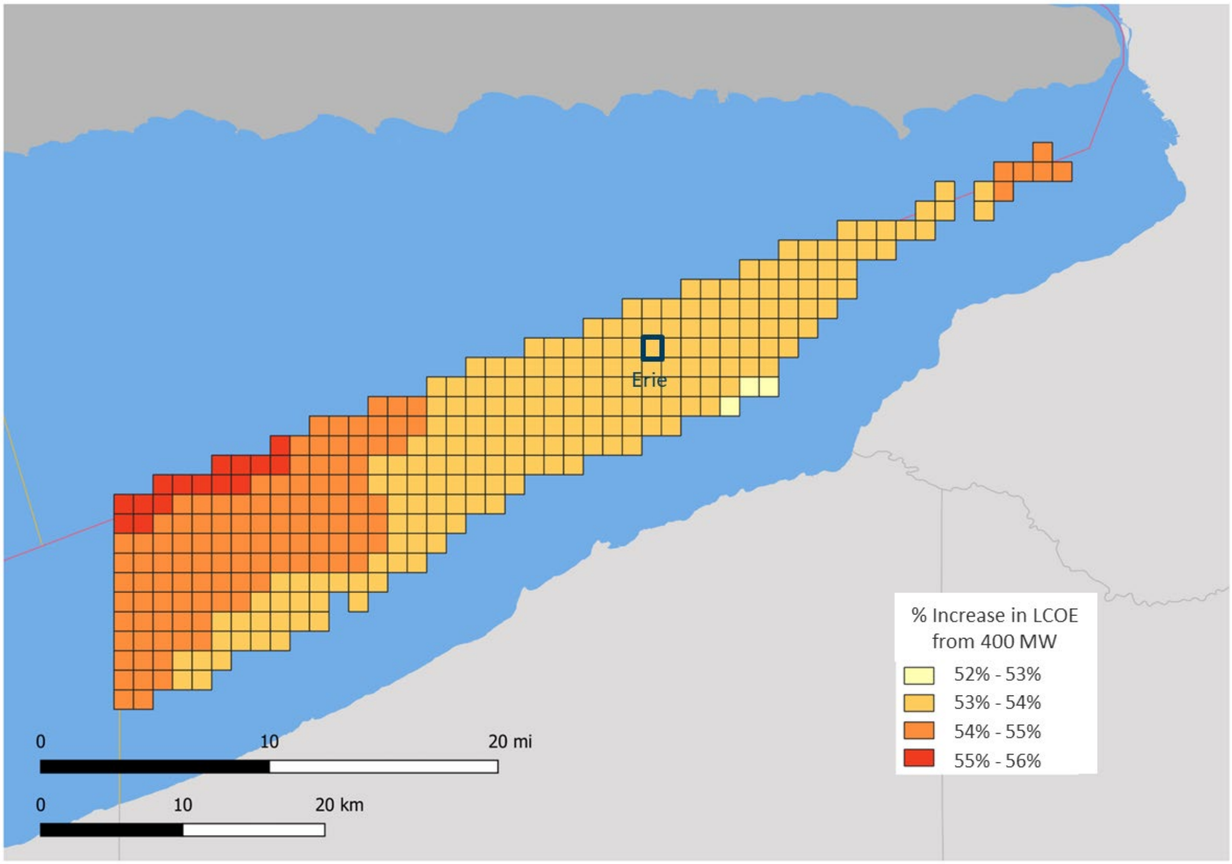


Figure 12. Change in Modeled LCOE in 2030 for Floating Wind in New York State Waters of Lake Ontario as Plant Capacity Increases from 400 MW to 800 MW

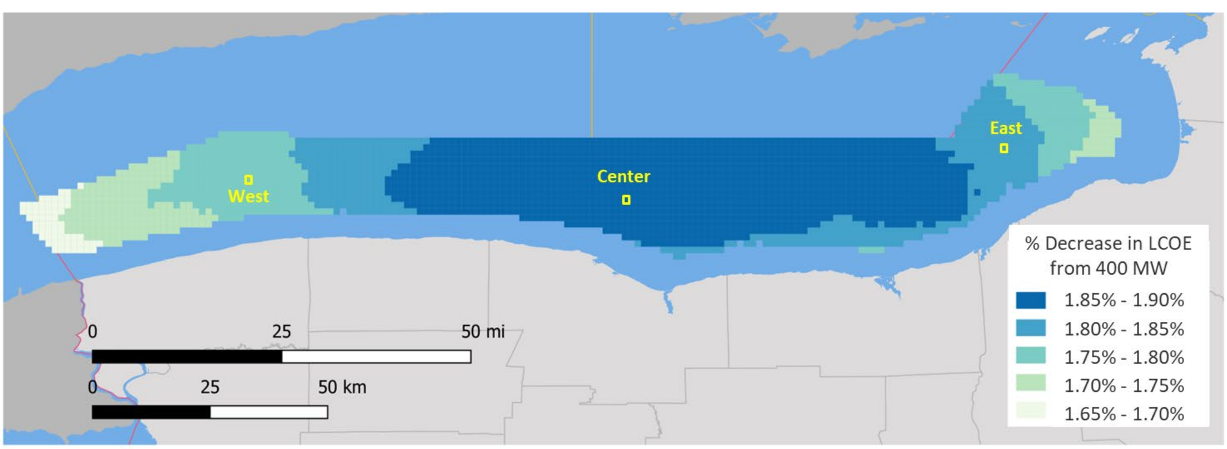


Table 11. LCOE for a 100-MW Wind Power Plant on Lake Erie and 800-MW Plants on Lake Ontario

	Erie	Ontario West	Ontario Center	Ontario East
Plant Capacity	100 MW	800 MW	800 MW	800 MW
2030 LCOE	$152/MWh	$104/MW	$98/MWh	$98/MWh
% Change from 400-MW plant	+53%	-1.8%	-1.9%	-1.8%

3.6 Opportunities to Further Reduce Cost for Great Lakes Wind

The analysis presented herein provides a baseline for assessing the cost of wind energy generation on the Great Lakes in the New York lakes based on current conditions. The derived cost reductions from learning include effects such as technology innovation, maturing supply chains, and turbine upsizing. Some of the effects included in this learning rate are:

- **Lower specific power rotors (and turbine technology improvements):** The 6 MW power curve used in this analysis has a specific power of 320 watts/m^2 which is probably higher than the optimum specific power for this region. A larger rotor is probably more optimal in this region given the lower extreme wind and wave conditions.
- **Regional collaboration with other states and Canada:** The current study assumed relative isolation from similar activities that may be underway in other states and Canada but leveraging these developments to achieve a larger industrial scale and to access ports, vessels, infrastructure, and facilities that may be in close proximity to the NYS sites of interest could yield substantial savings.
- **Supply chain synergies, industrialization, and economies of scale** can be exploited as the offshore industry develops along the Eastern seaboard. Overlaps among the wind plant components and required skillsets in the labor force could enable Great Lakes wind to leverage the multibillion-dollar investments being made in the Atlantic region.

The assumptions made were generally conservative and developers and the State of New York may find more creative technology solutions. Some areas that could result in further cost reductions include the following:

- **Larger turbines:** The 6 MW turbine size assumed for both lakes is based on conservative estimates of available crane capacity. This is not a hard limit, and especially for quayside assembly, larger turbines are feasible. This could be realized in Lake Ontario for floating systems and in Lake Erie if float-out concepts are developed. Larger turbines can have a large impact on project cost.
- **Larger plant size:** As was demonstrated, a larger plant size can lower total project cost per unit of energy. These economies of scale can be even more significant if multiple projects can leverage the local supply chains.

- **Innovations to improve accessibility and maintenance in winter months:** The technology knowledge base for offshore wind turbines in ice climates is limited but as the industry matures in this area the cost to operate and maintain these turbines is likely to decrease further. This study assumes generally that the currently available OpEx methods will be used. Lower average and extreme wave heights than ocean sites may provide further cost savings not accounted for in this study.
- **Proximity to grid:** Retiring thermal electric plants in the Great Lakes region and high population densities provide a relatively high number of interconnection opportunities that could lower interconnection costs relative to other regions.
- **State Policy and incentives:** State policy has driven the market for offshore wind in the United States and additional targeted state policy could accelerate the maturity of Great Lakes wind. Incentives such as grant funding for port development could stimulate growth of local economies and provide the infrastructure necessary for wind energy development.

There are also factors that could result in higher costs. One key assumption in our cost model is that wind plants are developed at commercial scale. The diversity of small, experimental demonstration or pilot-scale projects and their funding mechanisms makes it difficult to estimate costs for a generic pilot project; however, they typically have significantly higher costs than commercial-scale projects. Another area in which our assumptions may lead to an underestimate of future costs is OpEx. The learning rate for OpEx does not separate the effects of turbine upscaling from other sources of cost savings.

Many of the assumptions, both conservative and optimistic, that we made in the course of this cost modeling study resulted from a lack of data or commercial examples of appropriate technology. Future research in Lake Erie and Lake Ontario could help to provide better estimates of the impact of ice on power production and turbine availability during the winter months. Substructure cost estimates would benefit from engineering studies specific to the lakebed conditions and ice-structure interactions that are expected in each lake. A more detailed assessment of costs and benefits associated with specific alternatives for infrastructure improvements—including upgrades to ports and the transmission grid—would be valuable not only for wind energy development in the Great Lakes but also for other industries that use these facilities such as shipping, fishing, and land-based electric generation.

4 Conclusions

We considered a range of scenarios for wind energy development in the Great Lakes, including CODs of 2030 and 2035, plant capacities between 100 MW and 800 MW, fixed-bottom foundations in Lake Erie, and floating substructures in Lake Ontario. For 400-MW wind plants with a COD of 2030, LCOEs range from \$96/MWh to \$118/MWh, decreasing to between \$89/MWh and \$110/MWh for wind plants with a COD of 2035. LCOE increases by approximately 50% for smaller wind plants with a capacity of 100 MW, while there is a modest decrease in LCOE for 800-MW wind plants.

The range of LCOEs is similar across both Lakes Erie and Ontario; however, we observe some differences in the LCOE components between the two lakes. Modeled CapEx values are higher for floating wind plants on Lake Ontario, with a median value of \$4,140/kW in 2030 compared to \$4,050/kW for fixed-bottom wind plants on Lake Erie. CapEx is expected to decrease slightly more rapidly for floating technology by 2035 than for fixed-bottom wind plants. OpEx, in contrast, may be lower for floating wind plants than fixed-bottom wind plants as a result of greater challenges for winter access on Lake Erie as well as the need for specialized vessels for major repairs. Capacity factors fall within a similar range on both lakes, with slightly higher values projected on Lake Ontario.

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