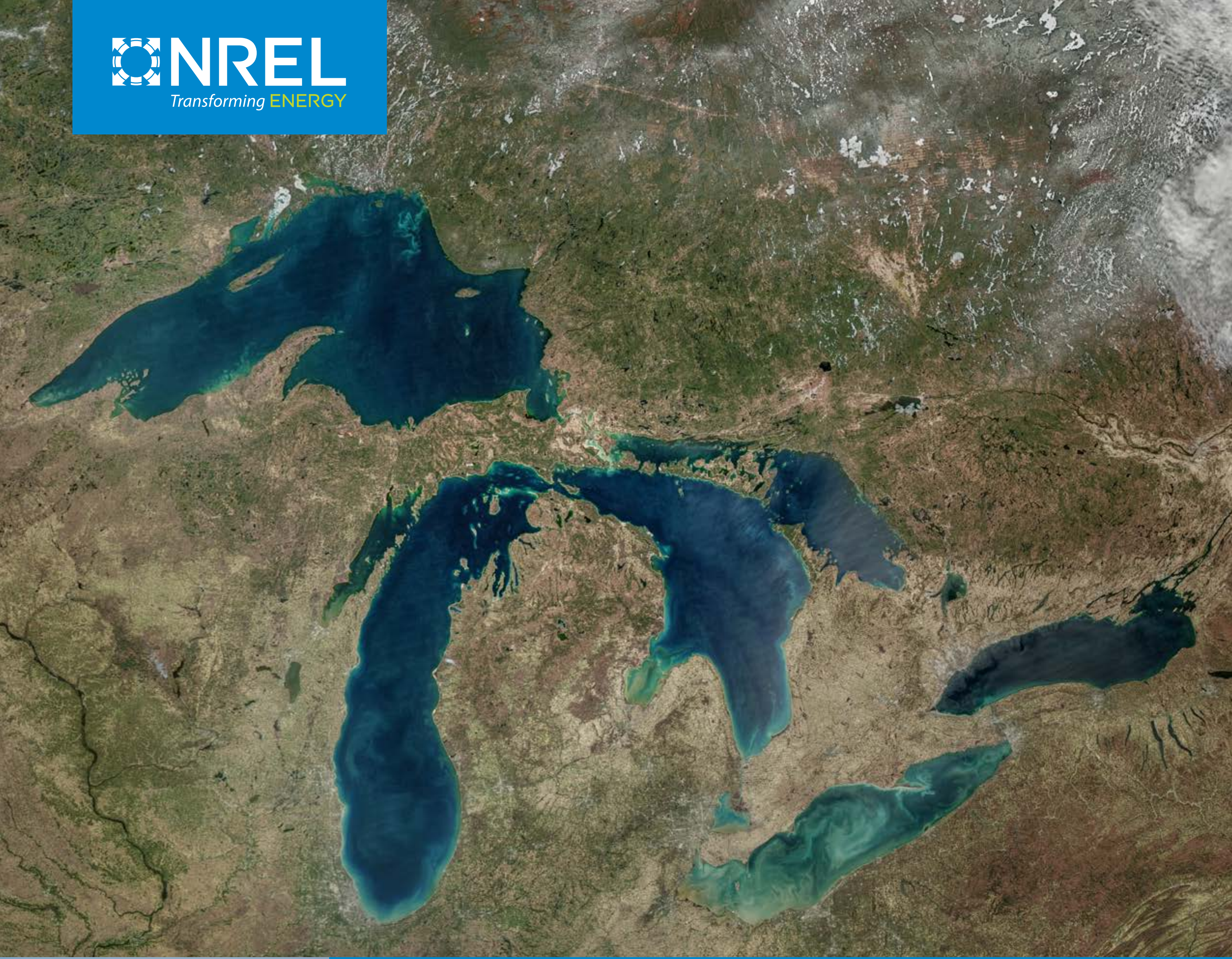

Great Lakes Wind Energy Challenges and Opportunities Assessment

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Walter Musial,[1] Rebecca Green,[1] Ed DeMeo,[2] Aubryn Cooperman,[1] Stein Housner,[1] Melinda Marquis,[1] Suzanne MacDonald,[1] Brinn McDowell,[1] Cris Hein,[1] Rebecca Rolph,[1] Patrick Duffy,[1] Gabriel R. Zuckerman,[1] Owen Roberts,[1] Jeremy Stefek,[1] and Eduardo Rangel[1]

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Suggested Citation

Musial, Walter, Rebecca Green, Ed DeMeo, Aubryn Cooperman, Stein Housner, Melinda Marquis, Suzanne MacDonald, Brinn McDowell, Cris Hein, Rebecca Rolph, Patrick Duffy, Gabriel R. Zuckerman, Owen Roberts, Jeremy Stefek, and Eduardo Rangel. 2023. *Great Lakes Wind Energy Challenges and Opportunities Assessment*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-84605. https://www.nrel.gov/docs/fy23osti/84605.pdf.

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5000-84605
March 2023

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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Inset photo of Suomen Hyötytuuli's Tahkoluoto offshore wind farm in Pori, Finland, photo by N.N. for Suomen Hyötytuuli

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Acknowledgments

The authors would like to extend thanks to Dan Beals and Nate McKenzie from the U.S. Department of Energy Wind Energy Technologies Office for directing this research. Thanks also to Patrick Gilman, Jocelyn Brown-Saracino, and Monica Maher (Wind Energy Technologies Office) for their support and strategic guidance.

The authors would also like to thank the following reviewers and contributors from the National Renewable Energy Laboratory: Brian Smith, Paul Veers, Amy Robertson, and Eric Lantz.

This report was peer-reviewed by a diverse group of Great Lakes wind energy industry stakeholders including developers, manufacturers, state government representatives, nongovernmental organizations, academics, and regulators. Peer reviewers include Doug Bessette (University of Michigan), Chris Winslow (Ohio Sea Grant/Ohio State University), Nicole DiPaolo (BlueGreen Alliance), Capt. George Haynes (Lakes Pilots Association, Inc.), Henrik Stiesdal (Stiesdal), Jifeng Peng (University of Alaska), Jia Wang (National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory), John Brand (Advisian), Dave Karpinski (Diamond Offshore Wind), David Devereaux (Independent Electricity System Operator), Michael Whitby (Bat Conservation International), Sarah Courbis (Advisian), Stacy Schumacher (Wisconsin Public Service Commission), Carolyn Heeps (FredOlsen SeaWind), and Jeff Kehne (Magellan Wind).

In addition, we would like to acknowledge the technical project management support from National Renewable Energy Laboratory staff including Setareh Saadat, and document editing by Sheri Anstedt, and communications support from John Frenzl and Jen Grieco.

List of Acronyms

AEP	annual energy production
ATB	Annual Technology Baseline
BGEPA	Bald and Golden Eagle Protection Act
CapEx	capital expenditures
DLC	design load case
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EMF	electromagnetic field
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FCR	fixed charge rate
FORCE	Forecasting Offshore wind Reductions in Cost of Energy
FWS	U.S. Fish and Wildlife Service
GLERL	Great Lakes Environmental Research Laboratory
GLFC	Great Lakes Fisheries Commission
GLRI	Great Lakes Restoration Initiative
GLWC	Great Lakes Wind Collaborative
GW	gigawatt
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IEC	International Electrotechnical Commission
IESO	Independent Electricity System Operator
IRA	Inflation Reduction Act of 2022
kW	kilowatt
kV	kilovolt
LCC	line commutate converter
LCOE	levelized cost of energy
LEEDCo	Lake Erie Energy Development Corporation
m	meter
m/s	meters per second
MBTA	Migratory Bird Treaty Act
MISO	Midcontinent Independent System Operator
MBTA	Migratory Bird Treaty Act
MW	megawatt
MWh	megawatt-hour
NCF	net capacity factor
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
NOWRDC	National Offshore Wind Research and Development Consortium
NREL	National Renewable Energy Laboratory
NRWAL	National Renewable Energy Laboratory Wind Analysis Library
NYISO	New York Independent System Operator
NYSERDA	New York State Energy Research and Development Authority
O&M	operations and maintenance

OpEx	operational expenditures
ORBIT	Offshore Renewables Balance-of-System and Installation Tool
PJM	PJM Interconnection LLC
PNNL	Pacific Northwest National Laboratory
POI	point of interconnection
ReEDS	Regional Energy Deployment System (model)
reV	Renewable Energy Potential Model
SEER	U.S. Offshore Wind Synthesis of Environmental Effects Research
TLP	tension-leg platform
USACE	U.S. Army Corps of Engineers
VSC	voltage source converter
W	watt
WETO	Wind Energy Technologies Office
WTIV	wind turbine installation vessel

Executive Summary

The United States has embarked on a pathway to achieve a 100% carbon-emissions-free electricity sector by 2035 and zero carbon emissions nationwide by 2050. Wind energy, both land-based and offshore, is expected to be a principal contributor, with offshore wind currently gaining a foothold in U.S. oceanic regions. Most offshore wind energy activity has been driven by individual states and boosted by federally-supported initiatives. Offshore wind energy resource potential in the Great Lakes region[1] is estimated to be substantial and in proximity to large energy loads where wind energy expansion could be strategically important in enabling these states to achieve their clean-energy goals (Musial et al. 2016).

Key initiatives provided by the Biden administration may also help reach state and federal clean-energy goals. For example, on September 15, 2022, the U.S. Department of Energy (DOE) announced the Floating Offshore Wind Shot™, which targets cost reductions of 70% down to $45 per megawatt-hour. The administration also announced that it will advance lease areas in deep waters to deploy 15 gigawatts (GW) of floating offshore wind capacity by 2035 (DOE 2022). These initiatives focus primarily on federal waters, but wind energy resource assessments of the Great Lakes, which are in state waters, estimate 160 GW of fixed-bottom resource potential and about 415 GW of resources suited for floating wind. Moreover, in five of the eight Great Lakes states, the lake-based wind energy resource potential exceeds the state's annual electricity consumption, illuminating a potentially large opportunity for transitioning to renewable energy.

Despite the positives, many issues associated with wind energy development in the Great Lakes region will require solutions that are different from those developed in ocean states, and industry learnings in these nearby ocean states may not address the unique deployment issues. As a result, technology readiness and cost reduction for Great Lakes wind energy generation is likely to be delayed relative to other regions without a substantial, targeted research campaign, infrastructure planning and investment, and proactive stakeholder engagement at all levels. Failure to conduct the necessary research to lower Great Lakes wind costs in the near term could limit its contribution to the nation's decarbonization goals.

The overall objective of a research plan like the one described in this report is to identify a commercial pathway for Great Lakes wind energy that begins before 2035. To ensure that prospective development of that wind energy is conducted efficiently, safely, and coordinated in the best interests of the local residents and stakeholders, DOE's Wind Energy Technologies Office tasked the National Renewable Energy Laboratory (NREL) to address the fundamental steps to:

- Gain an improved understanding of offshore wind energy's development potential in the Great Lakes
- Identify the key issues that need to be resolved for this potential to be achieved
- Define a comprehensive research plan to address and resolve these issues.

[1] "Great Lakes wind" is defined as offshore wind turbines that generate energy from wind over the Great Lakes (versus wind that is generated from the ocean, known as ocean-based or offshore wind).

This report presents the results of NREL's effort to address these steps.

The authors based the research approach on a comparison of two scenarios: the current technology scenario (Current Scenario) and the advanced research and technology scenario (Advanced Research Technology Scenario). The Current Scenario represents the current status of Great Lakes wind energy, which is based on existing technology and a knowledge base limited to mostly offshore wind energy industry experience in ocean-based states. The Advanced Research Technology Scenario provides the pathway for commercial competitiveness by targeting research solutions for specific Great Lakes barriers. This scenario includes larger wind turbines, proven floating Great Lakes wind energy technology, resolution of icing and ice loading issues, successful mitigation of any environmental and human-use issues, understanding of regulatory processes, establishment of robust supply chains, and more. The recommended research activities described in this report could potentially form the basis for a comprehensive research and development program focused on enabling large-scale commercial deployment of Great Lakes wind energy (Figure ES-1).

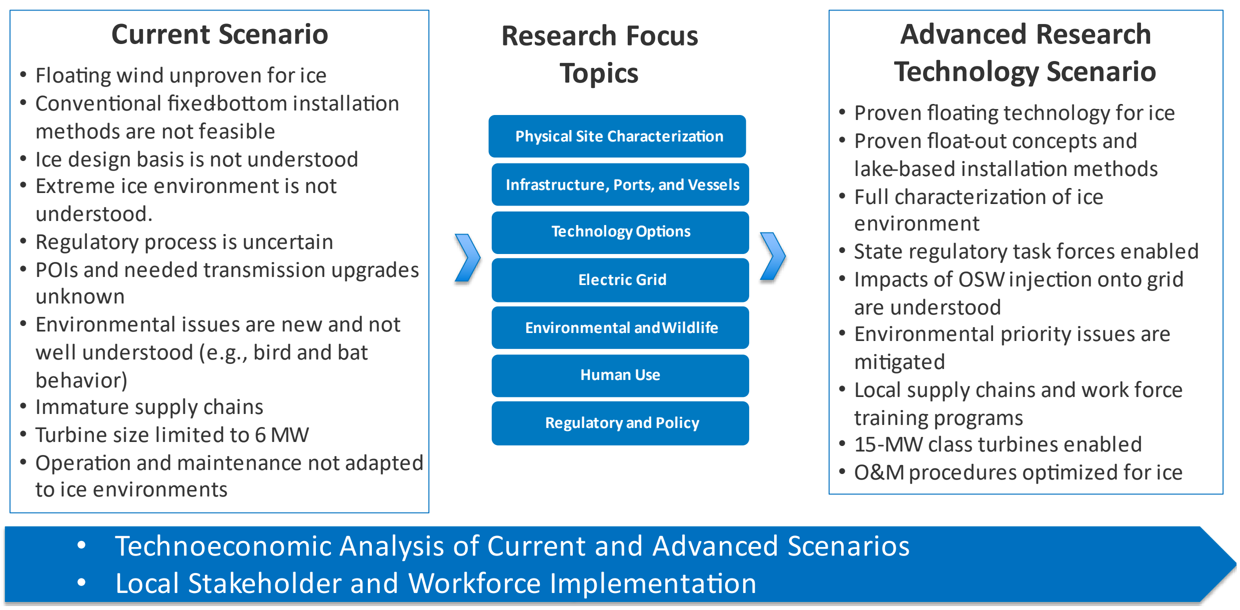

Figure ES-1. Approach to remove deployment barriers through advanced research and development

Drawing from the experience of NREL staff and external experts, we identified the following key research areas:

- Physical site characterization
- Infrastructure, ports, and vessels
- Technology options
- Electric grid interconnection and integration
- Environment and wildlife

- Human use
- Regulatory and policy
- Technoeconomic analysis (crosscutting)
- Local stakeholder and workforce implementation (crosscutting).

For each of these research topics, we identified and described major research challenges that need to be addressed and resolved if Great Lakes wind energy is to advance efficiently. Then we prioritized the challenges and identified recommended research activities to address them. We also characterized these challenges and the recommended research activities based on the level of current knowledge, estimated funding required, and time frame required to conduct the research. Most research activities will require follow-up efforts beyond the scope of this study. Therefore, the aim of this study was to identify research needs rather than to address them herein. However, in some cases, initial findings were developed that highlighted key issues (e.g., techno-economic cost analysis), revealing that follow-up work is still needed to obtain more accurate results.

This comprehensive study comprises the following high-priority research activities summarized below:

- **Physical site characterization.** Includes assessing the wind energy resource (Figure ES-2), icing conditions and impacts, lakebed features, and water currents. Because the lakes contain fresh water, the ice that forms is stronger and harder than in the ocean, which presents challenges for designing support structures. Specifically, design load conditions consistent with current state-of-the-art offshore wind structures do not account for loading caused by freshwater ice. Also, the soft lakebed sediments and shallow bedrock present challenges for foundation and anchor design. In addition, certain industrial activities along the shores of the Great Lakes and their tributary rivers have deposited heavy metals and toxic chemicals in layers of sediments that could potentially be disturbed when installing wind turbine substructures or cables. Therefore, we need to assess how these activities may impact the continued health of the lakes and the integrity of drinking water supplies.

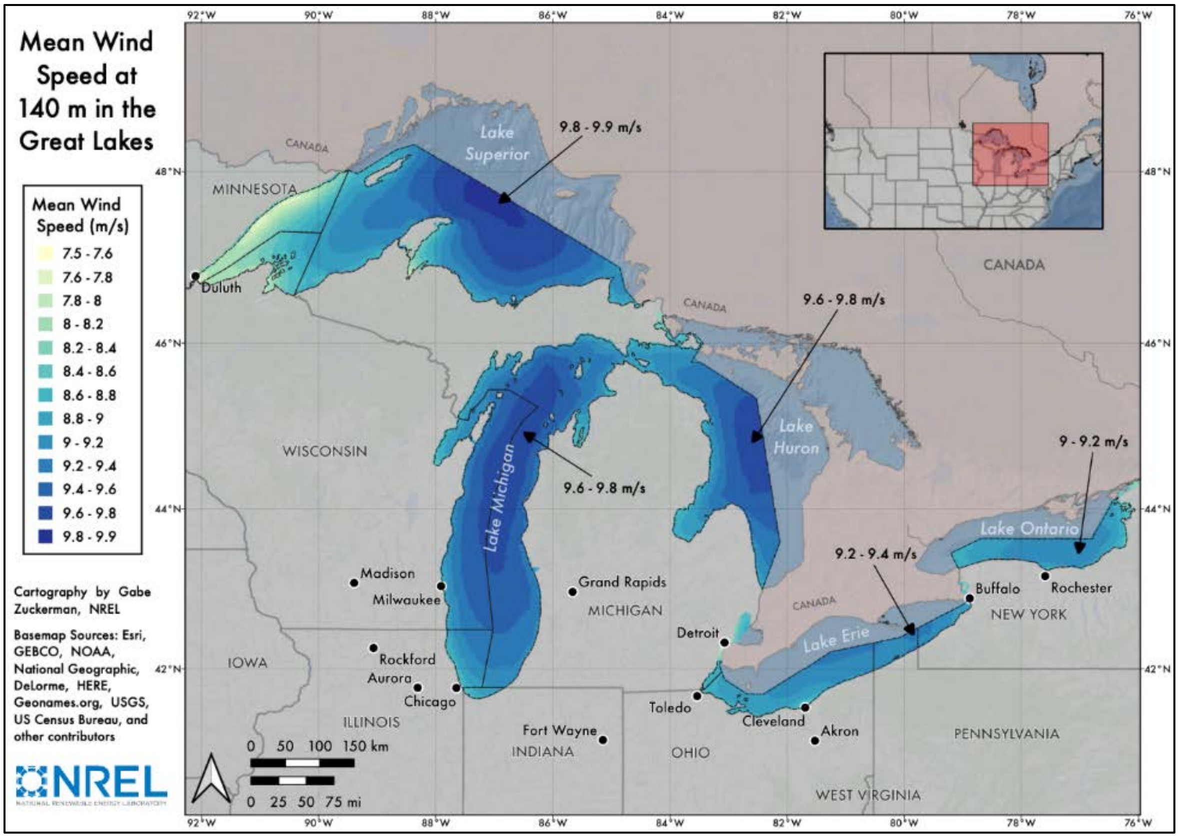

Figure ES-2. Mean wind speed of the Great Lakes at 140 meters (m) above ground level. ***Map generated with data from Bodini et al. (2021)***

Note: m/s – meters per second

- **Infrastructure, ports, and vessels.** Includes assessing the current limitations imposed by the existing locks network and estimating additional needs based on wind technology type (fixed bottom or floating). Large wind turbine installation vessels or other heavy-lift vessels cannot be brought into the lakes due to width and draft constraints through the locks of the St. Lawrence River, and these large vessels do not currently exist in the Great Lakes. As a result, an inventory of the vessels on the Lakes is needed which includes their upgrade potential to support Great Lakes wind energy development, with an assessment of the critical vessel needs. Overall, the current Great Lakes infrastructure is not yet able to support wind energy development, especially with the increased demands for installing and maintaining the new class of 15-megawatt (MW) wind turbines. Identifying the resources needed to deploy these offshore wind turbines is essential to realizing economies of scale and the associated economic benefits for the region.
- **Technology options.** Includes addressing the needs and prospects for fixed-bottom and floating foundations and larger turbines, as well as developing the infrastructure and supply chain needed to manufacture, transport, install, and maintain this equipment. Designs for fixed-bottom foundations, floating substructures, and wind turbines need to be reviewed and revised to account for icing impacts. These impacts include ice floe and ice sheet collisions with towers and substructures, as well as possible build-up of spray ice on turbine blades that can lead to increased and unbalanced loads. Note, the

overlapping issues related to transportation, construction, and logistics are tied closely to both the infrastructure, ports, and vessels and technology options research activities.

- **Electric grid interconnection and integration.** Includes identifying points of interconnection to the existing electric power network and assessing their power-handling capacities. Most electric grid and interconnection issues for the Great Lakes are similar to other offshore wind energy regions, but global experience indicates that grid infrastructure can cause significant development delays if not addressed early. Results will depend on plans for retiring existing coal plants, upgrading regional transmission assets that are underway, and adding transmission assets. We identify several prospective points of interconnection in this report, but further assessment of their capacities will require detailed investigation based on established power-system modeling tools used within the electricity sector. The electrical interconnection challenge is exacerbated by the fact that the existing power grid in the Great Lakes region—particularly in the more heavily populated areas near Lake Erie and Lake Michigan—is very congested. As a result, regional transmission and related electrical infrastructure must be upgraded, regardless of the degree of wind energy development in the lakes. The potential for alternative end-use scenarios such as green fuel production and storage have been considered and could be a key development for the Great Lakes given the existing grid congestion but generally were not considered a high-priority research topic because these technologies will be needed at a later stage but are not critical to initiating Great Lakes wind energy.
- **Environment and wildlife.** Includes conducting research to better understand the environmental risks associated with potential Great Lakes wind energy development, identify solutions for minimizing those risks, and inform low-impact siting and mitigation strategies that help ensure the benefits of wind projects outweigh the costs. The Great Lakes region provides important breeding, foraging, and resting areas for resident and migratory species. Millions of birds and bats migrate through the area every year as part of the Atlantic and Mississippi Flyways. Numerous other wildlife species also live in the region, including fish, invertebrates, and other aquatic and terrestrial species, all of which rely on healthy lake waters for food and habitat. Priority research needs include assessing and minimizing risk of potential bat and bird collisions with wind turbines, effects on fish ecology and aquatic resources (e.g., potential spread of invasive species due to installing new physical structures), and ecosystem-level effects of various stressors (including food webs and contaminants).
- **Human use.** Includes research to develop strategies for coexistence of potential Great Lakes wind energy development with residents and tribes in the United States and Canada that live in the region. Many of these stakeholders are coastal landowners and user groups who enjoy views and activities in the Great Lakes. Furthermore, the Great Lakes represent the world's largest source of fresh water, providing drinking water to more than 40 million people in the United States and Canada (National Oceanic and Atmospheric Administration 2019). The lakes are also home to activities like sportfishing, birding, recreational boating, use of beaches, and park visitation. Priority research needs include characterizing and minimizing viewshed impacts, mitigating drinking water impacts (including assessing sediment disturbance and mapping of known sediment contamination), and mitigating recreational and commercial use impacts, including for boaters and fisheries.

- **Regulatory and policy.** Includes assessing each states' laws and policies to better understand Great Lakes wind energy development and potential barriers. For each affected state, a thorough review is needed of offshore leasing processes, along with understanding of the major federal, state, and utility permitting and regulatory authorizations that would likely be required for wind energy projects in territorial waters. Across the Great Lakes, critical information is needed on the key regulatory and permitting processes, agencies involved, lessons learned from similar projects, and recommendations to ensure an efficient permitting process that would allow for maximum input and consideration from the public and other key stakeholders. Priority research needs include assessing: leasing processes in each state; state and federal permitting processes to document regulatory regimes and identify potential legal barriers (including developing regulatory road maps for each state); environmental and international regulations (including uncertainties with the Migratory Bird Treaty Act); and infrastructure and physical regulations (related to electrical interconnection, cables, ports, and vessels).

In addition to providing research recommendations, this report includes a crosscutting analysis of Great Lakes wind energy costs, with cost being an important factor that influences whether and when to develop wind energy projects. The two scenarios examined in this analysis illustrate the potential for targeted research to reduce the cost of wind energy in the Great Lakes by 2035. According to the modeling methodology used, the levelized cost of energy of Great Lakes wind energy is expected to reach between $75/megawatt-hour (MWh) and $129/MWh by 2035, under the Current Scenario. Under the Advanced Research Technology Scenario, the expected 2035 levelized cost of energy range drops to between $62/MWh and $89/MWh (Figure ES-3). The cost is, on average, 27.5% lower for any given location under the Advanced Research Technology Scenario. This level of cost reduction is significant, and although it is short of the DOE Floating Wind Shot™ target, it could likely accelerate deployment of Great Lakes wind energy while increasing the total opportunity for states in the region to meet their decarbonization and clean energy targets using a local resource.

The competitiveness of Great Lakes wind energy with other renewable sources such as land-based wind and solar was beyond the scope of this study; therefore, it has not been determined if our estimated cost reductions are sufficient to incentivize Great Lakes wind energy development as a least-cost option. However, as the renewable energy transition continues, the decreasing availability of low-cost, land-based wind energy sites may become the long-term driver for cost competitiveness, and Great-Lake-based options may become increasingly more attractive.

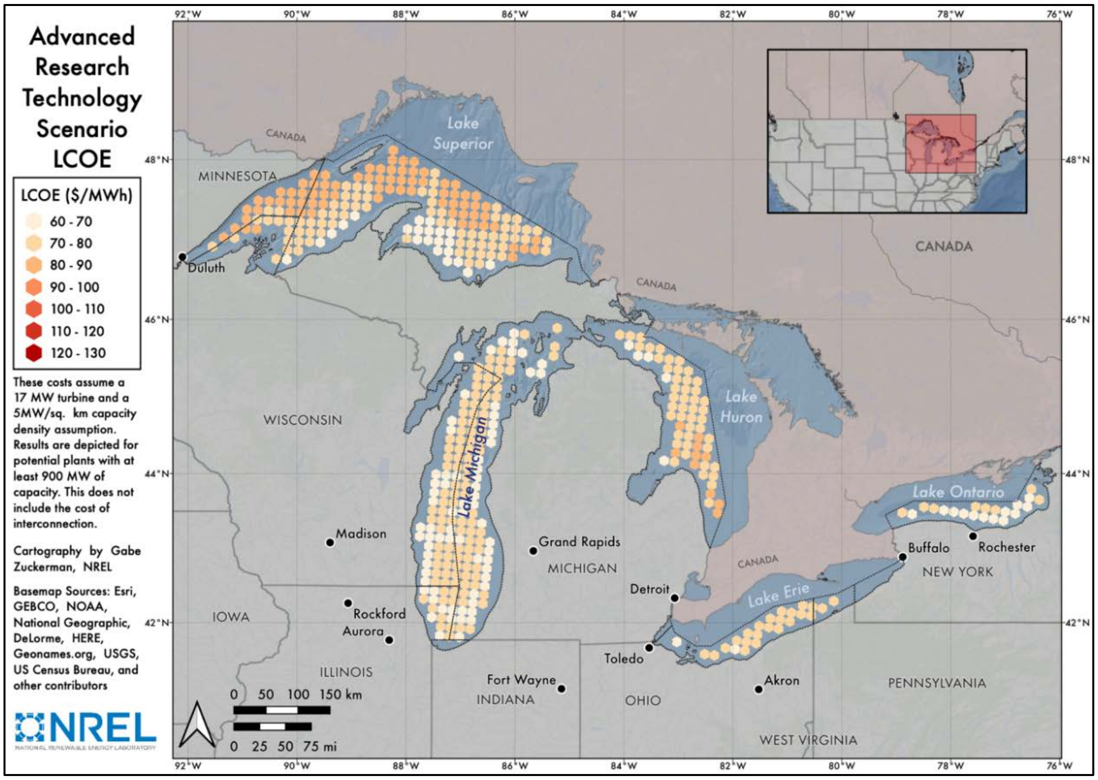

Figure ES-3. Modeled levelized cost of energy (LCOE) in 2035 for the Advanced Research Technology Scenario

This report also considers stakeholder and workforce engagement activities. Early and ongoing engagement with key stakeholders is a necessary step in establishing an efficient wind energy development and regulatory process. Proactively identifying and preparing to engage key stakeholders in the Great Lakes region will close information gaps, expand workforce opportunities, and integrate equity into the development process. Activities that are needed in the region include implementing energy equity and justice activities, enhancing regional research capabilities by investing in research coordination and building on existing local research efforts, disseminating information to stakeholders to ensure access to accurate and relevant Great Lakes wind energy information, and performing analysis to identify potential labor opportunities and barriers to Great Lakes wind energy deployment.

Finally, this study draws some limited insights from a recent preliminary study of the U.S. energy system by NREL that looks at the nation's challenges of achieving the 2035 and 2050 decarbonization targets and the conditions under which offshore wind energy might play a key role (Mai et al. 2022). The Mai et al. study assumptions are generally representative of the Current Scenario for Great Lakes wind energy, but its results should not be viewed as a prediction of actual deployment. The study used the NREL Regional Energy Deployment System model, and its modeling assumptions incorporated many uncertainties and simplifications, but it provides the best-available relative comparison of the interplay among all energy options under various decarbonization scenarios. Figure ES-4 shows that the model estimated over 40 GW of offshore wind energy in the Great Lakes by 2050, in a 95% grid decarbonization scenario (95% Core scenario). In this scenario, Great Lakes development does not begin until after 2042, given the availability of lower-cost, zero-carbon resources in the region up until that point.[2]

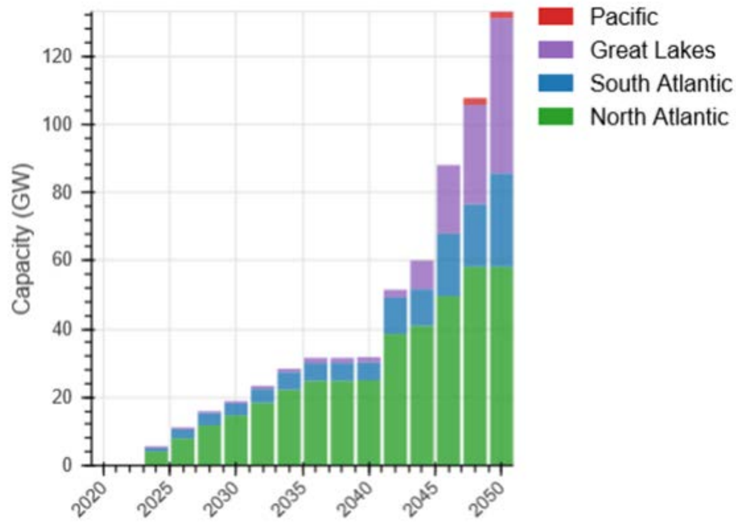

Figure ES-4. Regional offshore wind energy deployment in a 95% grid decarbonization-by-2050 scenario. ***Graph reproduced from Mai et al. (2022)***

This modeled scenario does not take into account all the challenges—e.g., logistics and infrastructure—that would need to be addressed to achieve such deployment levels, but it does indicate that Great Lakes wind energy could be needed to fully decarbonize states in this region. Similar spikes in offshore wind energy deployment were not observed in the modeled data for other regions where lower-cost, zero-carbon resources were more widely accessible by the model. This foresight into the possible scarcity of land-based renewable options in the Great Lakes region suggests that some intervention to lower costs may be prudent to accelerate Great Lakes wind energy technology deployment and avoid high energy prices. Additional modeling is needed to assess the actual deployment requirements of all technologies with current policy and advanced technology impacts represented.

Overall, we find that there is real opportunity for Great Lakes wind energy resources to not only contribute to the regional energy mix and the economic growth of the region but help achieve long term national clean energy goals. To develop an informed Great Lakes wind energy strategy, further investments in targeted research are needed by federal and state agencies to address the high-priority topics outlined in this report. Consideration should be given to forming a Great Lakes wind energy advisory group with members from across sectors. We also recommend organizing a Great Lakes wind energy workshop to encourage discussion and information exchange amongst key stakeholders and tribes.

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[2] The cost assumptions that were used in the Regional Energy Deployment System (ReEDS) Core 95% decarbonization scenario were roughly equivalent to the Current Scenario used in this report. One key difference is that all the ReEDS deployment took place in shallow water. That depth is not considered a valid constraint in this report and future ReEDS analysis will take that into account.

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1 Introduction

Globally, commercial-scale offshore wind energy deployment is developing rapidly with over 50 gigawatts (GW) installed across Europe and Asia by the end of 2021. In the United States, only 42 megawatts (MW) have been deployed so far but key indicators such as over 40 GW in the domestic project pipeline, 39 GW of state policy commitments, 24 offtake agreements, and over 900 MW under construction provide evidence that the nascent U.S. offshore wind industry is already a major player in the world market. Continued cost declines relative to other technologies in this global market may help drive a broader demand for offshore wind domestically as one of the primary clean energy options.

U.S. offshore wind energy markets are developing first in the north and mid-Atlantic states where densely populated energy load centers are close to highly energetic ocean wind areas. Large, utility-scale, electric-generating projects can be built offshore while avoiding high real estate costs and minimizing siting issues that would be encountered on populated land. The value of offshore wind energy is further enhanced by added social and economic benefits including high-paying job growth and health benefits associated with clean power.

U.S. offshore wind energy adoption has been primarily incentivized through state policies in the northeast and mid-Atlantic regions and backed by federal policy that set a goal of deploying 30 GW of offshore wind energy by 2030 (The White House 2021). Recently, federal incentives have been added through the Inflation Reduction Act of 2022, which will support longer-term offshore wind projects as far out as 2035. There are 23 U.S. states that border an ocean and today most of those states are considering offshore wind as a future energy option, motivated by federal and state policies that favor electrification to displace fossil-fuel use.

There are also eight states that share a border with one of the Great Lakes.[3] The Great Lakes comprise an area of 94,250 square miles (244,160 square kilometers [km^2]) and contain about 21% of the available fresh water on the planet. Based on 2019 data from the U.S. Energy Information Administration (EIA), these eight states account for 1,310 million metric tons (MMT) of energy-related carbon-dioxide emissions, which is about 25% of the total 5,158 MMT U.S. emissions (Table 1).

[3] New York shares a border with both the Atlantic Ocean and the Great Lakes.

Table 1. Million Metric Tons of Energy-Related Carbon-Dioxide Emissions by Sector in Great Lakes States in 2019 (Source: EIA State Energy Data System and EIA Calculations Made for This Analysis)

State	Commercial	Electric Power	Residential	Industrial	Transportation	Total
Illinois	15.4	58.2	25.7	36.3	67.8	203.4
Indiana	6.2	75.8	9.0	46.1	39.1	176.1
Michigan	11.8	54.6	21.5	18.9	52.4	159.2
Minnesota	7.4	22.9	10.2	17.9	33.7	92.1
New York	22.9	21.4	35.7	9.0	79.8	169.0
Ohio	12.4	67.5	18.4	37.8	60.7	196.7
Pennsylvania	12.0	75.1	19.5	50.5	61.7	218.7
Wisconsin	6.7	33.3	10.8	13.3	30.7	94.8
Totals	**94.7**	**408.7**	**150.9**	**230.0**	**425.8**	**1,310.1**

These Great Lakes states are generally characterized by their northern latitudes, moderately populated land areas, industrial/agricultural economies, and shared watershed. As greenhouse gas emission reduction plans evolve, Great Lakes states will likely continue to seek renewable energy solutions that are economically, environmentally, and socially compatible with their geographic constraints, demographics, and energy use patterns. Great Lakes wind energy could provide a gigawatt-scale option to be considered as part of each state's prospective renewable energy mix.

The investigation into Great Lakes utility-scale wind energy has already begun. In 2012, the U.S. Department of Energy's (DOE) Wind Energy Technologies Office (WETO) funded the Lake Erie Energy Development Corporation (LEEDCo), under their Advanced Technology Demonstration program, to develop a 21-MW, pilot-scale project 7 miles north of Cleveland, Ohio, on Lake Erie (DOE undated). This project, known as "Icebreaker," is still under development. In its quest to be the first freshwater wind farm in the United States, it has encountered many unique challenges related to ice design, power offtake contracting, social opposition, and state regulatory impediments.

In October 2020, the New York Public Service Commission directed the New York State Energy Research and Development Authority (NYSERDA) to fund a study to investigate the feasibility of generating power from winds on the Great Lakes. This study was led by the National Renewable Energy Laboratory (NREL) and is titled the *New York Great Lakes Feasibility Study*, which investigated wind energy development in New York State waters off Lake Erie and Lake Ontario (NYSERDA 2022a). The NREL study found no insurmountable barriers to Great Lakes wind energy development. Accompanying the release of the NREL study, NYSERDA published a white paper that recommended New York not pursue Great Lakes wind energy before 2030. While the White Paper focused on the near-term, it went on to conclude, "taking no action now does not mean there may not be an opportunity to advance Great Lakes Wind at some point in the future. The resource may become a feasible contributor to New York State's goals in the future as the State advances toward its mid-century goals…" (NYSERDA 2022b). New York's near-term view of the Great Lakes wind resource is consistent with this study, which sees little carbon reduction opportunity before 2030, but possibly a substantial long-term regional opportunity for energy, the economy and the environment. To realize this full potential, this report indicates that the critical research challenges need to be addressed upfront.

The United States has embarked on a pathway to achieve a 100% carbon-emissions-free electricity sector by 2035 and net-zero carbon emissions nationwide by 2050. Wind energy, both land-based and offshore, is expected to be a principal contributor to achieving these goals. Ocean-based offshore wind has made extensive progress in Europe and is beginning to gain a foothold in the north and mid-Atlantic regions. This early domestic activity has been driven primarily by economic-development and environmental-quality goals established by individual states, followed by state procurement policy, and augmented by recent federally supported initiatives.

Great Lakes wind energy also shows substantial resource potential, but the technological challenges and uncertainties are presently greater than for ocean-based offshore wind which has full access to global supply chains. Like the states along the Eastern Seaboard, most states in the Great Lakes region also have goals to substantially reduce their carbon footprint (see Section 9 – Regulatory and Policy), but no procurement mechanisms exist yet. These states already include significant land-based wind and solar resources in their energy portfolios and future energy plans, but large-scale expansion of these resources may eventually become constrained by land-availability and human-use conflicts, such as proximity to existing habitats and infrastructure, which will drive up costs. Consequently, wind energy expansion into the waters of the Great Lakes could potentially enable these states to achieve their clean-energy goals while providing significant local economic benefits, improved energy security, and cleaner air.

Key to achieving these goals is federal support provided by the Biden administration help advance renewable energy technologies such as floating offshore wind. On September 15, 2022, DOE announced a Floating Offshore Wind Shot ™, which targets cost reductions to $45 per megawatt-hour (MWh). In addition, the administration announced it will advance leasing in deeper waters to enable the deployment of 15 GW of floating wind energy capacity by 2035 (DOE 2022). These actions are very relevant to the Great Lakes which has a resource potential estimated at 160 GW for fixed-bottom and about 415 GW for floating wind energy (Lopez et al. 2022).

However, research and development are needed to address unique issues associated with wind energy development in the Great Lakes that are different than ocean-based offshore wind. Without a substantial, targeted Great Lakes wind energy research campaign and proactive stakeholder engagement that articulates the social, economic, and environmental benefits for communities at all levels, technology readiness and cost reduction for energy generation in this region is likely to be delayed relative to other coastal regions. Failure to conduct the necessary research to lower wind energy costs in the near term would make it unlikely for it to contribute to the nation's decarbonization goals by 2035, but more importantly, inaction could potentially raise long-term energy prices in Great Lakes states by holding costs high while other lower-cost renewable energy options become scarce.

This report aims to provide a comprehensive assessment of the research needs and unique challenges of developing Great Lakes wind energy across the region. This energy resource may be needed in states constrained by high population densities where growth of utility-scale land-based wind energy and solar projects could be limited by siting issues due to existing use conflicts.

Wind energy from the Great Lakes may have several benefits including:

- High average wind resources (up to and exceeding 9 meters per second [m/s]) close to load centers, which can support state and federal efforts to decarbonize electricity and electrify space heating, transportation, and other activities that currently burn fossil fuels
- The ability to build gigawatt-scale, lake-based wind energy projects that cannot be built on land due to existing use conflicts and high real estate costs
- High-paying jobs that can revitalize waning industrial communities through direct Great Lakes wind energy project planning, construction, operations and maintenance (O&M), upgrade of ports and vessels, and the potential influx of new factories to support domestic manufacturing
- Dominant state control of the leasing, permitting, and approval processes that can have significant socio-economic benefits associated with greater local control over distribution of community assistance, lease sales revenues, and potential energy generation royalties relative to the federal regulatory process that governs offshore wind.

However, the challenges of Great Lakes wind energy development are significant; therefore the purpose of this report is to describe those challenges and possible research activities that could make this energy source competitive with others in the region.

1.1 Study Scope and Key Research Questions

The primary objective of this study is to identify the most important research needed to enable Great Lakes wind energy to become commercially feasible and to contribute on a large scale to help decarbonize regional energy supplies.

The study does not conduct extensive research on any single topic but focuses broadly on identifying critical challenges. To meet this objective, a significant understanding of the current state of technical and deployment barriers was necessary so that the priority challenges could be described in sufficient detail to result in actionable recommendations.

The key research questions that this study attempted to answer are:

- What is the potential opportunity for future large-scale wind energy deployment in the Great Lakes, and under what conditions?
- What are the near-term and long-term challenges in the Great Lakes associated with realizing that opportunity? For example, will Great Lakes wind energy become viable under existing policies with currently projected technology evolution or will additional policies such as those associated with deep decarbonization be needed?
- What are the near- and long-term challenges in the Great Lakes associated with commercial-scale lake-based wind energy?
- What level of effort is required to address the challenges and what is the expected time frame to address them?

- What are the economics of key deployment scenarios and how would they be affected by targeted research to resolve the challenges; how would that research affect the business case?
- What actors are best placed to address these challenges?

In this work, these questions are considered, but due to the complexity of the energy system and the uncertainty of policy impacts, the results should be considered as preliminary, may not fully address the entire problem, and are subject to modification under the scrutiny of further investigations. In general, the long-term deployment scenarios considered include some expectation that responses to climate change mitigation and decarbonization will play a role in determining Great Lakes wind energy deployment capacity and timelines. The intent is that this report will help guide those responses.

The pathway to commercialization in the wind industry has traditionally been to advance technology through prototype testing and demonstration projects before embarking on a full utility-scale project (gigawatt scale), like the ones underway in the Atlantic. The offshore wind energy industry has matured to the point where incremental technology changes such as larger wind turbines no longer trigger an automatic need for small-scale demonstration because the core technology is still bankable. But one can point to the immediate benefits that were realized through the 30-MW Block Island Wind Farm in Rhode Island in 2016, which increased the industry's confidence significantly and, in part, spurred the present wave of offshore wind energy development in the United States. Similar pilot projects are planned in the state of Maine, for example, where the 11-MW New England Aqua Ventus plans to be the first U.S.-based floating offshore wind turbine deployed. Even though over 200 MW of floating wind energy has been installed globally, real-world demonstration in the United States may be needed to lower project risk and convince stakeholders that those risks are manageable.

While smaller pilot-scale projects can cost over three times more per unit of energy, they are often necessary in new environments to alleviate fear and gain the needed trust from all invested groups. Due to the higher cost, the challenge with these flagship projects is to find investors willing to sponsor them when the bottom line may not be bankable. Some demonstration projects have been financed with the help of federal funding (e.g., Offshore Wind Advanced Technology Demonstration Projects), or through the equity provided by a developer interested in the larger, long-term technology investment. In the Great Lakes, the technology challenges identified herein can be partially addressed with the proposed research agenda under the Advanced Research Technology Scenario, but ultimately there will need to be some deployment to demonstrate that the technology is safe, efficient, and can be integrated in harmony with the Great Lakes ecosystems and culture. The most effective support mechanism for these pilot-scale projects has come through state procurement incentives that serve their overarching clean-energy and economic-development targets (Musial et al. 2022). However, these mechanisms to enable real-world demonstration are not considered in detail under this study but should be part of the larger conversation and included in the next steps going forward.

1.2 Prior Research on Great Lakes Wind Energy

The history of interest in Great Lakes wind energy development dates back over a decade and has involved a variety of stakeholders. In April 2006, DOE and NREL sponsored the "Great Lakes Offshore Wind Gathering" in Toledo, Ohio, which set in motion significant regional and state interest in offshore wind energy development on Lake Erie. For example, the Great Lakes Wind Collaborative (GLWC) was active between 2008 and 2013 as a multisector coalition of wind energy stakeholders working to facilitate the sustainable development of wind energy in the binational Great Lakes region; the GLWC is no longer active. However, the Great Lakes Commission maintains a website with links to the GLWC's convening and research activities, including for example, those related to pelagic bird stakeholder engagement, understanding impacts on fisheries and aquatic resources, and assessing ecological impacts of wind energy. The GLWC's *Best Practices for Sustainable Wind Energy Development in the Great Lakes Region* (GLWC 2011a) offers 18 different preferred practices and policies related to Great Lakes wind energy, covering all phases of the process including development, operations, and decommissioning. These materials offer a historical perspective and repository of information that can help inform wind energy development in the region moving forward.

In Michigan, the Great Lakes Wind Council was created in January 2009 as an advisory body within the state's Department of Energy, Labor and Economic Growth to examine issues and make policy recommendations related to offshore wind energy development in state waters. The council's first report recommended criteria and buffer areas to be used in mapping the favorable areas for offshore wind energy development in Michigan's Great Lakes (Michigan Great Lakes Wind Council 2009). The report stated that development in only a small fraction of the state's Great Lakes could produce significant amounts of wind energy while recognizing that Michigan lacked adequate regulatory guidelines to govern such development. The council organized and hosted a variety of public engagement activities during spring and summer of 2010, leading to its second report, which further refined its data collection and initial recommendations for the most and least desirable areas for Great Lakes wind energy development (Michigan Great Lakes Wind Council 2010). The council also provided input and recommendations on a legislative framework for leasing Michigan's Great Lakes bottomlands and permitting offshore wind energy systems. However, Scandia Wind proposed a large project off the shore of Western Michigan in 2010 that received public backlash and never came to fruition.

Other notable early state activities include Illinois's Lake Michigan Offshore Wind Advisory Council, formed in 2011 and Wisconsin's 2009 Study Group on offshore wind, formed by the Wisconsin Public Service Commission at the request of then-Governor Jim Doyle's Task Force on Global Warming. The task force convened working groups on engineering and economics, and wind turbine technology (Wisconsin Public Service Commission 2009). These efforts were exploratory and have not resulted in a sustained commitment to date.

In August 2009, LEEDCo was created by the Great Lakes Energy Development Task Force in Ohio as a public-private nonprofit partnership devoted to catalyzing the offshore wind energy industry in the Great Lakes region, with an award to LEEDCo from DOE. LEEDCo's Icebreaker Wind project (Figure 1) led to a series of technical studies to appropriately design and engineer the wind array, as well as a series of environmental studies, to inform compliance with the National Environmental Policy Act (NEPA) and other federal and state statutes. Technical considerations have involved wind turbine generator type and foundation design, as well as the substation interconnect, along with studies of wind resource data and Lake Erie ice formation. Environmental studies have focused on both water and biological resources, including considerations for water quality, birds and bats, fishes, and aquatic and terrestrial protected species. In August 2022, the outcome of a lawsuit was determined in favor of the Icebreaker project with the Ohio Supreme Court ruling that the Ohio Power Siting Board—despite claims to the contrary—had obtained enough information about the potential impacts on birds and bats before issuing a permit for the project. LEEDCo can now resume selling the remainder of the power from the project and work on renewed construction planning. Regardless of the outcome of the Icebreaker project, the technical, regulatory, and environmental lessons learned to date are invaluable for future projects.

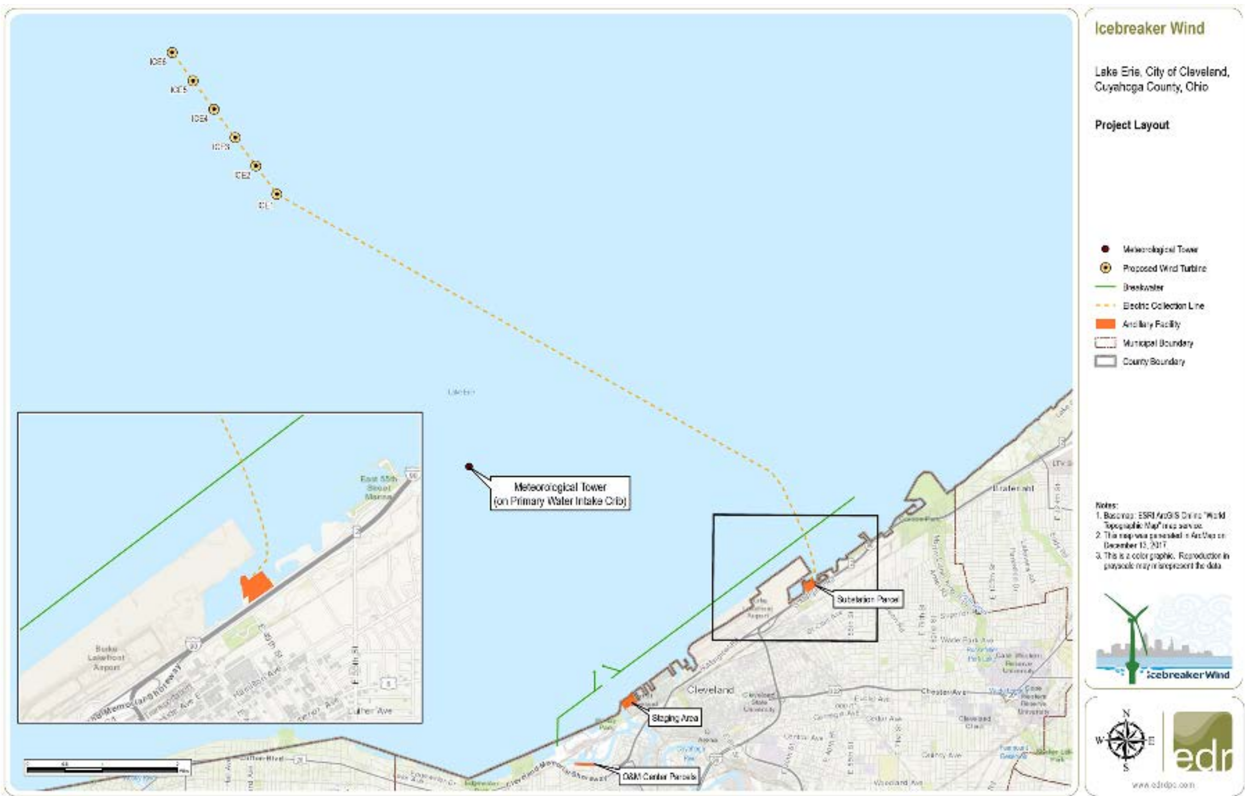

Figure 1. The 21-MW LEEDCo Icebreaker project layout in Lake Erie; located 7 miles north of Cleveland

In 2012, DOE awarded two projects aimed at creating engineering computer models for interaction of fixed-bottom offshore wind turbines (not floating) with surface ice for use with common engineering simulation tools (NREL 2014). The projects were awarded to the University of Michigan and DNV to develop the IceDyn and IceFloe modules, respectively, using ice properties in the Great Lakes to verify the model parameters. The primary lesson learned was that ice loading will likely play a significant role in designing offshore support structures for wind turbines located in the Great Lakes and a deeper assessment of icing conditions will be critical to making design calculations in the region.

In 2019, NREL was funded by the National Offshore Wind Research and Development Consortium (NOWRDC) to develop a validated national offshore wind resource data set with uncertainty quantification, which specifically incorporated all U.S. regions, including the Great Lakes. The new wind resource product is now available for the Great Lakes through the DOE Open Energy Data Initiative (Bodini et al. 2021). These new data reaffirm that the wind resource quality in the Great Lakes has a high potential for energy production with most sites exceeding an annual average wind speed of 9 m/s.

Other awards through NOWRDC are providing a variety of wind power plant technology advancements that may have relevance to the Great Lakes (NOWRDC 2022), such as those related to novel foundation design and installation methods that may potentially avoid the need for vessels that are not available in this region. Examples of relevant awarded projects include Texas A&M University's "Vibratory-Installed Bucket Foundation for Fixed Foundation Offshore Wind Towers," DEME Offshore US's "Tri-Suction Pile Caisson TSPC Foundation Concept," RCAM Technologies' "A Low-Cost Modular Concrete Support Structure and Heavy Lift Vessel Alternative," and Esteyco's Self-Installing Concrete Gravity-Base Substructure Sizing for 15MW Turbine."

In addition, the Great Lakes wind energy technical potential was recently assessed as part of the DOE-funded "Spatial Analysis for Wind Technology Development" project. For this research, NREL determined the offshore wind energy technical potential for the contiguous United States, including the Great Lakes, using high spatial resolution layers and a technical siting model (Lopez et al. 2022). Siting considerations for wind energy projects included competing uses, existing infrastructure, protected areas, and more. Wind turbine assumptions in the modeling included use of a 15-MW-class turbine and a capacity density of 5.3 MW/km^2. Based on the assessment, and using an open-access scenario, fixed-bottom and floating offshore wind technical potential in the Great Lakes was estimated at 160 GW and 415 GW, respectively. This study reaffirmed that the resource quantities in the Great Lakes are substantial and can potentially provide some states with a major clean energy option.

In October 2020, the State of New York Public Service Commission issued an order requiring a feasibility study of Great Lakes wind energy. In response, NREL, Advisian, and Pterra/Brattle conducted the *New York Great Lakes Wind Feasibility Study* (Figure 2). The study helped determine the feasibility of wind energy development in the New York State waters of Lake Erie and Lake Ontario through a framework that balanced environmental, maritime, economic, and social issues with consideration of market barriers and costs (NYSERDA 2022a). The study involved data gathering, information synthesis, technical analysis, and development of recommendations for next steps to help New York State plan for potential future Great Lakes wind energy development. The study team for this DOE report used many of the same NREL staff as for the NYSERDA report, which enabled the efficient transfer of knowledge from the New York study.

A white paper was then prepared by NYSERDA that summarized the technical studies conducted in the feasibility study and provided additional analysis of the role of Great Lakes wind energy projects in the context of New York State's renewable energy portfolio and pathways to reach the state's Climate Act goals (NYSERDA 2022b). The paper concluded that Great Lakes wind energy currently does not offer a unique, critical, or cost-effective contribution toward the achievement of New York State's Climate Act goals in the near term using a time horizon of 2030. The paper did not assess potential contributions from Great Lakes wind for longer time horizons. Its results also do not apply directly to other Great Lakes states that have different needs and resources. For example, New York State has access to offshore wind on the Atlantic coast, which is not a resource available to the other Great Lakes states.

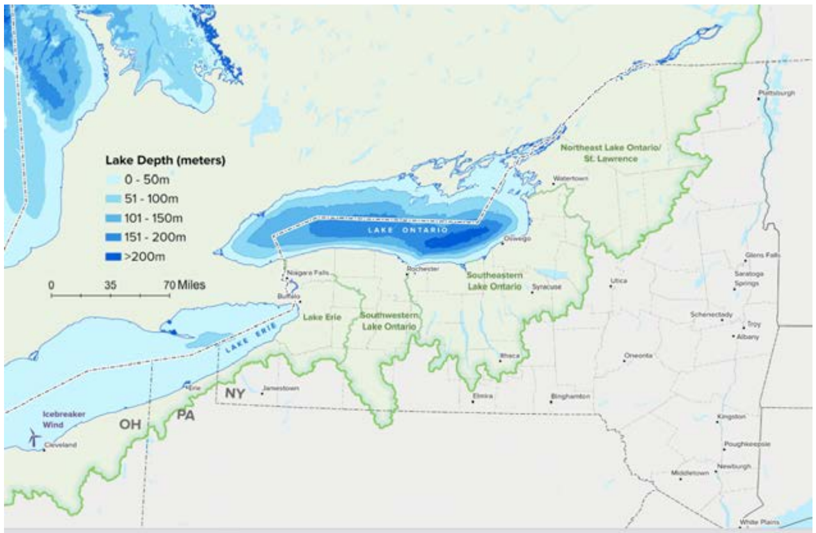

Figure 2. Region of interest for NYSERDA's *New York Great Lakes Wind Energy Feasibility Study* (NYSERDA 2022a)

From an environmental perspective, minimizing wind turbine collision risk for birds remains one of the top priorities for offshore wind energy development globally (Green et al. 2022). The DOE-funded U.S. Offshore Wind Synthesis of Environmental Effects Research (SEER) project, a collaboration between NREL and the Pacific Northwest National Laboratory (PNNL), recently summarized bat and bird interactions with offshore wind turbines. The team identified monitoring approaches including visual surveys, radar, cameras, strike indicators, tracking devices, and acoustic detectors to determine species composition, assess behavioral changes, and detect collisions (SEER 2022). In addition, DOE is funding multiple studies through its offshore wind market acceleration projects that use different approaches to monitor avian and bat collisions with offshore wind turbines. For example, with DOE funding, PNNL and the United States Geological Survey are developing a radar system capable of measuring bird and bat abundances and behaviors at offshore locations. The radar system will be integrated with one of DOE's lidar buoys and validated with auxiliary measurements from thermal cameras, acoustic monitors, weather radar (Next Generation Weather Radar, or NEXRAD), and human observers. Ultimately, the technology aims to produce a radar and buoy system capable of monitoring bird and bat activity above open water and demonstrate its performance by collecting baseline data in the Great Lakes.

1.3 Report Organization

This report describes the priority research challenges and associated recommended research activities that are needed to advance Great Lakes wind energy development.

- Section 2 describes the methodology and technical approach.

- Sections 3−9 provide a detailed discussion of each of the major research topic areas including a description of the current situation and the desired outcome (or end state) that could be achieved if the research challenges are successfully addressed. For each research topic, the highest priority research challenges are described and a set of possible activities to address those challenges is outlined.

- Sections 10 and 11 describe crosscutting activities involving cost modeling, local stakeholder activities, and workforce development. The techno-economic assessment describes the detailed spatial cost analysis conducted for all five lakes for two scenarios: (1) the current situation, and (2) an advanced research technology scenario that estimates the cost reduction benefits of a mature Great Lakes wind energy industry enabled by an advanced research agenda in 2035.

2 Technical Approach

The general methodology for the study focuses on removing barriers to Great Lakes wind energy development by addressing high-priority challenge areas and comparing current and advanced research technology scenarios (before and after) that are informed by research focus topics (Figure 3). The Current Scenario represents the situation in the Great Lakes today with many constraints that limit the optimum application of the best offshore wind technologies that have been developed over the past two decades in ocean-based projects. This scenario includes constraints on large vessels navigating into the lakes and uncertainties about the lake ice environment. These constraints limit wind turbine size and constrain the use of established global offshore wind supply chains, thereby contributing to higher costs. Generally, the Current Scenario relies on knowledge gained through the larger global and domestic offshore wind industry coupled with present data and information that are available but limited.

The research focus topics contain the specific priority challenges that we identified in this study. Although most of these priority challenges have yet to be addressed, a successful program of research activities performed over the next several years can contribute significantly to the realization of the Advanced Research Technology Scenario and accelerated Great Lakes wind energy deployment. A successful implementation of the Advanced Research Technology Scenario will make the Great Lakes region self-sufficient and market-ready for gigawatt-scale projects using 15-MW-class wind turbines. Under the Advanced Research Technology Scenario, Great Lakes wind energy technology will likely be implemented sooner and at a lower cost, which will serve decarbonization strategies better and enable lower electricity prices regionally.

We conducted the detailed spatial technoeconomic cost analysis to contrast the economics of both scenarios in terms of levelized cost of energy (LCOE). Under the Advanced Research Technology Scenario outcome, the navigation issues into the Great Lakes are addressed by enabling technologies that can be implemented by infrastructure and vessels stationed on the lakes while resolving the high uncertainties that accompany the development of wind support structures (both floating and fixed bottom) that must survive the regional ice conditions. In addition, concerns about how Great Lakes wind energy development could potentially harm the environment will be assessed, addressed, and mitigated through siting choices and actions to avoid, minimize, restore, and/or offset potential impacts.

For each focus area, the study examined how Great Lakes wind energy deployment might be perceived by the local stakeholders and tribes. Stakeholders could be interested or concerned citizens, potential members of the future Great Lakes wind energy workforce, or technical experts and community leaders that are needed to conduct the identified research activities.

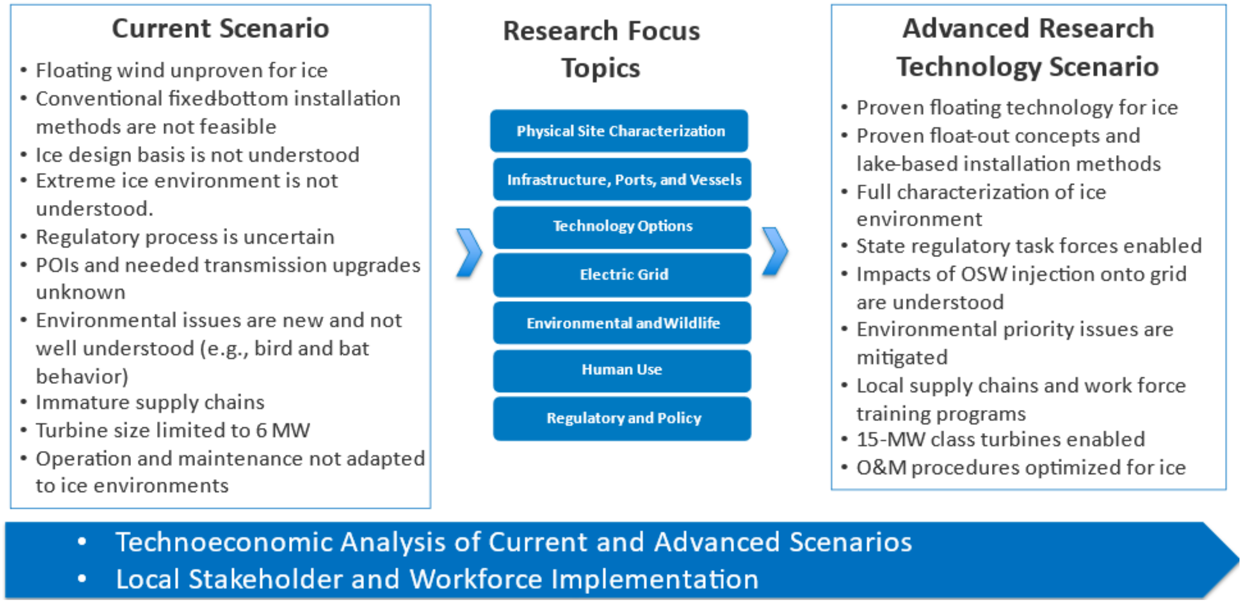

Figure 3. Approach to remove deployment barriers through advanced research and development

2.1 Current Status

There have been many past exploratory efforts to consider Great Lakes wind energy as an energy source as described in Section 1.2, but so far none have resulted in a sustained commitment. So far, most initiative have come from individual states, but a broad regional strategy does not yet exist.

The existence of annual freshwater surface ice introduces some new technological uncertainties, especially for floating wind turbines, which have not yet been demonstrated under those conditions. The narrow locks of the St Lawrence Seaway and the upstream canals limit some conventional installation and construction vessels from entering, which limits the feasible size of fixed-bottom wind turbines. Some unique environmental and social issues such as possible avian interactions, viewshed issues, possible toxins in the near-shore sediments need to be addressed for gigawatt-scale project deployment. Although the wind resource is excellent in terms of energy-generating potential, project capital costs may be higher initially due to these regional constraints, and project development may be later than in the Atlantic (while economic and regulatory issues are addressed). Yet, no insurmountable barriers have been identified in this study to ultimately render Great Lakes wind energy unfeasible.

2.2 Future Vision

The future vision for Great Lakes wind energy is quite positive. A future scenario that includes regional state support, Great-Lakes-specific technology research and development, regional domestic supply chains, and proactive engagement with other lake users, stakeholders, and tribes can result in cost reductions in line with ocean-based offshore wind sites. The research to be conducted and described herein will enable floating wind in four of the five lakes (Lake Erie being too shallow), with some advantages over fixed foundations because of the independence from heavy-lift wind turbine installation vessels (WTIVs), the primary constraint on wind turbine size and cost. One of the biggest cost reduction drivers is the potential to develop local logistics and supply chains and their inherent economies of scale. A future scenario would include the development and revitalization of regional factories, ports, and vessels that meet the needs of and provide self-sufficiency to the new Great-Lakes-based wind energy industry.

Mai et al. recently conducted a study that is summarized in "Determinants of Offshore Wind in a Future U.S. Energy System" (Mai et al. 2022). Based on this preliminary modeling of national decarbonization scenarios using NREL's Regional Energy Deployment System (ReEDS), results imply that Great Lakes wind energy will likely be needed to address national decarbonization targets. This implication is based on the core scenario prescribing 95% decarbonization by 2050. The scenario estimated 133 GW of offshore wind energy deployment nationally and the model predicted over 40 GW of wind deployed in the Great Lakes by 2050. While no significant deployment was predicted to happen initially, beginning in 2042, these large amounts of Great Lakes wind energy are chosen over other options, such as land-based wind energy and solar. This late surge may indicate that by the time it is finally adopted, lower-cost siting options for the other technologies have been depleted by the model and more expensive Great Lakes wind energy is deployed because the model had no other choices.

The state of the Great Lakes wind energy market that is represented by Mai et al. (2022) in the ReEDS assessment is less mature than other offshore regions of the country and the technologies and policies modeled are more representative of the Current Scenario. As a result, more work is needed to not only assess the cost thresholds for Great Lakes wind energy deployment under the Current Scenario (i.e., when the deployment of Great Lakes wind energy begins in the ReEDS model), but also how deployment is augmented under the Advanced Research Technology Scenario when recent policy changes are included. Generally, under the Current Scenario, Great Lakes wind energy costs will be higher and deployment will begin later than under the Advanced Research Technology Scenario.

Although the 40-GW deployment of Great Lakes wind energy does not predict future deployment, it does indicate that Great Lakes wind energy will likely need to be considered if national decarbonization targets are to be met (Mai et al. 2022). However, the benefits can be significant. As a hypothetical market reference only, a deployment level of 40 GW would generate about $150 billion in revenue and create thousands of high-paying jobs in the region. With the Advanced Research Technology Scenario and the new incentives recently authorized in the Inflation Reduction Act of 2022, it may be possible to significantly accelerate both cost reductions for Great Lakes wind energy and the initiation of deployment (see Section 10.6).

2.3 Identifying Research Topics and Challenges

The team identified the research topics described earlier by drawing from experience with ocean-based offshore wind energy project development, land-based wind energy deployment, electric power system expansion, and assessments of the major differences between the ocean and Great Lakes environments gathered from our past work in the region. Our research teams identified key challenge areas specific to their research topic area. For each challenge area, the teams defined a series of preliminary research activities aimed at addressing and resolving the key issues. This process included reviewing relevant literature, conducting initial interviews with external subject matter experts, and participating in discussions with team members to incorporate relevant experience.

2.3.1 Research Challenges

Recent NREL research conducted for NYSERDA to examine Great Lakes wind energy potential in the two Great Lakes bordering New York provided substantial background for this study (NYSERDA 2022a). That work suggested a preliminary list of research focus topics and associated research challenges within those topical areas. The research challenge descriptions were then refined based on interviews with topical experts, as well as based on additional background and experience from team members and past relevant project experience. The team also obtained additional input and perspective from regional stakeholders representing the regulatory, electric power, project developer, and technology sectors.

2.3.1.1 Prioritization

All the research activities identified and described in this report are important for advancing Great Lakes wind energy development. However, to assist program planners and managers in deciding which activities to pursue and in what order and to what extent, the study team prioritized the challenge areas and quantified the research activities in terms of cost and time to complete. First, the challenge areas are prioritized according to their importance on a scale of 1 to 3. Those with a priority ranking of 1 are issues that generally address all the following criteria, a priority ranking of 2 are issues that generally address two of the following criteria, and a priority ranking of 3 are issues that generally address one of the following criteria:

- **A barrier to deployment**—technological, political, regulatory, or other—with the potential to arrest Great Lakes wind energy development.
- An impact that will result in **unacceptably high Great Lakes wind energy costs** if the issue remains unresolved.
- An impact that affects a **large deployment area**, such as multiple lakes and a high potential for reduced Great Lakes wind installed capacity.

We assigned priority rankings based on the best judgment of the teams. The study focused on the highest-priority challenges, but ultimately some were ranked lower after some review. There are likely many more low-priority challenges that are not mentioned in this report because the study team assumed they would be discovered during the normal project development activities and solved as part of the developers' due diligence. Challenge areas were also characterized based on the level of existing relevant knowledge, which was based on the technical assessments made by the authors relative to the available literature on the Great Lakes and specifically regional wind energy. These judgements are subjective and can change in the light of further research but are meant to provide a rough baseline for future researchers on the relative amount of prior effort that is available to build upon.

2.3.2 Research Activities

The research activities identified and described in this report span a wide range of disciplines and issues. Typically, for each challenge area we recommend several specific research activities, but these recommendations should be considered preliminary and are not necessarily complete for a given topic. These activities include such topics as:

- Assessing site characterization, wind resource, lakebed features, and ice conditions
- Evaluating the capabilities and needs of ports and vessels for installation and maintenance

- Developing the supply chain
- Researching prospective opportunities and synergies with Canadian entities
- Assessing technology options, capabilities, and needs, including both fixed-bottom and floating systems
- Investigating electric power network points of interconnection, power handling capacity, and transmission expansion plans and needs
- Estimating project costs
- Determining environmental, wildlife, and human-use impacts, including examining viewshed and collaborating with fisheries
- Evaluating regulatory risks and mitigation
- Engaging the workforce.

For each challenge area, we identified qualified organizations that can conduct this needed research, but the names are not provided in this report. These organizations include marine operation contractors; wind technology manufacturers and suppliers; offshore wind energy developers; state agencies; independent system operators, regional transmission operators and electric utilities; environmental nongovernmental organizations; national laboratories; and research and academic institutions, among others. It may be helpful to enable these regional organizations to conduct this research as much as possible, as their ownership and participation may be critical to Great Lakes wind energy acceptance and success (see Section 11).

2.3.2.1 Level of Effort and Timelines

We characterized each research activity according to the estimated financial level of effort required to conduct the activity and the estimated time required for completion, based on experience with scoping similar types of projects in the past. The following bins were used for level of effort in dollars: <$200,000, $200,000−500,000, $500,000−$1 million, $1−$2 million, and >$2 million. The following bins were used for timelines: <6 months, 6 months–1 year, 1−3 years, 3−5 years, and >5 years. Note that these are roughly estimated ranges for financial effort and timelines, and they may vary based on future changes to research activity scope and tasks.

The level of effort and timelines for each challenge area should not be taken as the final word on the requirements for each challenge but as an approximate starting point. These estimates were based on the professional judgements of the authors, who are subject matter experts in their related fields. The values were also modified by the multiple reviewers who assessed these judgements and, in many cases, helped refine the original costs and durations. The numbers are subject to further change as the various needs come into sharper focus.

Table 2 lists the challenge areas that are discussed in Sections 3−9, in order of priority. Note there are 13 Priority #1 challenges out of a total of 33.

Table 2. Challenge Area Priority List

Challenge Title	Priority	Major Deploy-ment Barrier?	High Cost Impact?	Impacts Most Lakes?	Level of Knowledge
Characterize Surface Ice Extremes	1	✓	✓	✓	Medium
Characterize Ice Formation from Spray	1	✓	✓	✓	Medium
Assess Vessel Requirements and Solutions	1	✓	✓	✓	Medium
Assess Port Capacities and Solutions	1	✓	✓	✓	Medium
Advance Ice-Structure Interaction Modeling (for Fixed-Bottom and Floating Substructures)	1	✓	✓	✓	Medium
Develop Alternative Fixed-Bottom Substructure Designs and Installation Methods	1	✓	✓	✓	Medium
Develop Alternative Floating Substructure Designs and Installation Methods	1	✓	✓	✓	Medium
Assess Cable Design, Installation, and Maintenance (With Respect to Ice)	1	✓	✓	✓	Medium
Address Great Lakes Uncertainties in Bat and Bird Interactions with Wind Turbines	1	✓	✓	✓	Medium
Characterize and Address Viewshed Impacts	1	✓	✓	✓	Medium
Assess and Develop Avoidance and/or Mitigation for Drinking Water Impacts	1	✓	✓	✓	Medium
Implement State-by-State Leasing and Permitting Studies	1	✓	✓	✓	Low
Conduct Formal Coordination to Inform Decision-Making and Engage Stakeholders (e.g., Forming a Great Lakes Wind Energy Coordinating Group)	1	✓	✓	✓	Medium
Develop Design Basis for Great Lakes Wind Energy (for Fixed-Bottom and Floating Substructures)	1	✓	✓	✓	Medium
Adapt Operations and Maintenance Procedures for Great Lakes Conditions	2		✓	✓	Medium
Develop Cold-Climate Turbine Design Alternatives	2		✓	✓	Medium

Challenge Title	Priority	Major Deploy-ment Barrier?	High Cost Impact?	Impacts Most Lakes?	Level of Knowledge
Develop System Engineering Modeling Tools for Great Lakes Ice Climate	2	✓		✓	Low
Develop Supply Chain Strategies	2		✓	✓	Low
Evaluate Points of Interconnection and Transmission Needs	2		✓	✓	Medium
Assess and Compare High-Voltage Alternating Current (HVAC) vs. High-Voltage Direct Current (HVDC) Transmission Technologies	2		✓	✓	Medium
Assess Effects on Fish Ecology and Aquatic Resources (Native and Invasive Species)	2	✓		✓	Medium
Assess Ecosystem Effects of Various Environmental Stressors	2	✓		✓	Medium
Mitigate Recreational and Commercial Use Impacts for Fisheries	2	✓		✓	Medium
Assess Environmental and International Regulations	2	✓		✓	Medium
Assess Infrastructure and Physical Regulations	2	✓		✓	Medium
Implement Energy Equity and Justice Activities	2		✓	✓	Low
Perform Workforce Analysis	2	✓		✓	Medium
Characterize and Validate Wind Resource	3			✓	Medium
Characterize Lakebed and Sediments	3			✓	Medium
Characterize Water Currents	3			✓	Medium
Examine Additional Grid Opportunities	3			✓	Medium
Assess Canadian Infrastructure Opportunities	3			✓	Low
Enhance Regional Research Capabilities	3			✓	Medium

3 Physical Site Characterization

The physical environment of the Great Lakes is distinct in several ways from other sites where offshore wind turbines have been installed. Because the lakes contain fresh water, the ice that forms is stronger and harder than in the ocean, which can make it more difficult to design support structures. The soft lakebed sediments and shallow bedrock also present challenges for foundation and anchor design. Yet, the Great Lakes environment provides some advantages over the ocean, including a relatively mild wave climate in spring and summer, which could enable low-cost, innovative installation solutions and lower operations costs in those seasons.

3.1 Current Situation

3.1.1 Resource Assessment

The quality of the wind resource is a key determinant of the economic viability of a Great Lakes wind energy project. Both wind speed and demand for electricity exhibit daily, seasonal, and annual patterns. The value of Great Lakes wind energy may be higher if periods of energy production coincide with periods of high demand that are not met by other generation sources. Resource data are generally obtained from high-fidelity models, but validation of those models is necessary to ensure accurate predictions of performance.

NREL produced a new wind resource assessment[4] for the Great Lakes region using the Weather Research and Forecasting model (Skamarock et al. 2019). The data set covers 21 years (2000−2020) using 2-km spatial resolution at nine vertical levels up to 200 meters (m) from the surface. For more details on the Weather Research and Forecasting model parameters, see NYSERDA (2022a). Figure 4 shows the 21-year-mean wind speed at 140 m above ground level. The mean wind speed is greater than 8.5 m/s across most of the lakes, except near the western end of Lake Superior where mean wind speeds drop between 7.5 m/s and 8 m/s. The highest mean wind speeds are found in the upper three lakes, whereas Lake Erie and Lake Ontario have lower annual means. Wind speeds are generally higher near the center of each lake, farther from shore.

Table 3 compares the potential wind energy generation from the Great Lakes with electricity demand in states that border the lakes. We estimated the resource potential using a capacity density of 5 MW/km^2 throughout the U.S. waters of the Great Lakes, with no excluded areas other than a minimum distance of 3 miles from shore. The assumed capacity density is similar to that used in a recent analysis of offshore wind resource potential (Lopez et al. 2022) and close to observed values of intra-array turbine spacing in Europe. The amount of generating capacity installed per square kilometer within individual wind farms varies depending on wind turbine rating and layout; average capacity densities for European offshore wind farms are between 5.5 and 6 MW/km^2 (Deutsche WindGuard GmbH 2018). The potential capacity (in megawatts) in each state's waters was converted to an estimate of annual electricity generation (in terawatt-hours) using a power curve for a 5.5-MW wind turbine (representative of the Current Scenario) with losses as described in Section 10.3. The total retail electricity sales in 2020 (EIA 2022) are used to estimate electricity demand in each state. The ratio of potential generation to current demand (Table 3, far right column) indicates the opportunity for Great Lakes wind to contribute to meeting energy needs in each state. For example, Michigan's resource potential in the Great Lakes could supply up to 18 times its 2020 electric-generating demand, whereas resources from Indiana's state waters in Lake Michigan would only meet a maximum of 6% of its 2020 electric demand. The table shows that five of the eight Great Lakes states have resources that exceed their electric-generating capacity. These indicative values are a useful comparison for estimating the total opportunity by state for Great Lakes wind energy but are subject to many sources of

[4] Wind data are available for download from OpenEI (Bodini et al. 2021): https://data.openei.org/submissions/4500.

uncertainty, including the extent of the area in which offshore wind energy development may be permitted or prohibited, changing demand for electricity, and possible delivery of Great Lakes wind energy across state boundaries.

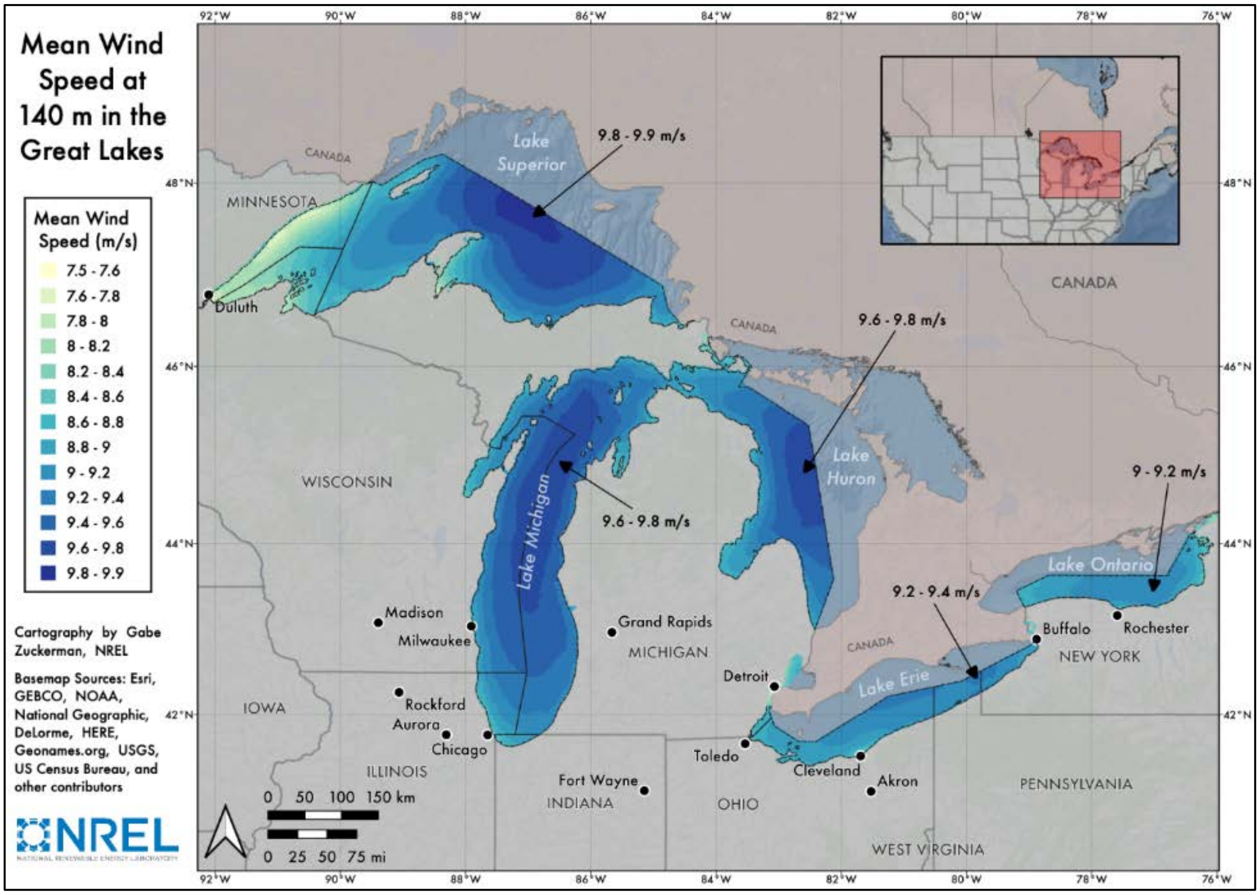

Figure 4. Mean wind speed at 140 m above water level. ***Map generated with data from Bodini et al. (2021)***

Table 3. Electricity Consumption and Offshore Wind Resource Potential in the Great Lakes Region

	Annual Electric Consumption (terawatt-hours)[5]	Great Lakes Wind Resource Capacity[6] (GW)	Potential Annual Energy Production (terawatt-hours)[5]	Potential Energy Production/ Current Electric Consumption
Michigan	97	390	1,821	1,877%
Wisconsin	67	97	447	667%
New York	140	40	177	126%
Ohio	143	36	159	111%
Minnesota	64	25	98	153%
Illinois	132	19	88	67%
Pennsylvania	140	6.4	28	20%
Indiana	97	1.3	6.0	6%

3.1.2 Generation and Load

Daily and seasonal changes in electricity generation are significant factors for assessing the value of the wind resource. Hourly loads and wind energy generation potential for a single site in each lake were analyzed over 1 year. We modeled busbar loads in 2030 for the Great Lakes region using NREL's Standard Scenarios Mid Case (Gagnon et al. 2021). Load profiles for Ohio, Michigan, Illinois, New York, and Wisconsin were averaged to approximate typical daily patterns in electricity demand in the Great Lakes region. Generation profiles for locations within each lake were estimated based on the wind speed at 112.5 m from March 2019 to February 2020 (Bodini et al. 2021) and converted into power output using the power curve for a 5.5-MW wind turbine and loss assumptions described in Section 10.

Figure 5 compares the seasonal average electricity load demand and Great Lakes wind energy generation potential in each lake, for each hour of the day. Loads in the Great Lakes region (solid black lines) have similar diurnal trends and magnitudes in the spring, fall, and winter, around 25% higher during the day than overnight with a peak near 6 p.m. (Figure 5). The summertime load peak is higher than in other seasons and occurs earlier in the day, near 2 p.m., which is likely to meet air conditioning needs. Net capacity factors across the lakes range from approximately 25% to 60%, with the highest capacity factor occurring in the winter and the lowest during the summer. The average capacity factor for all lakes is 52% in spring, 37% in summer, 55% in fall, and 58% in winter. Capacity factors are highest in the early morning and lowest in the late afternoon.

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[5] Total retail electricity sales in 2020 from EIA (2022).

[6] Resource capacity and annual energy production assume wind turbines are installed at locations beyond 3 miles from shore, with an array density of 5 MW/km^2 using 5.5-MW turbines (described in Section 10.3 under the Current Scenario).

Generation and load are highly out of phase in the summer, with generation peaking when demand is lowest and vice versa. In the other seasons, generation does not drop as low, or even increases slightly in the middle of the day during the period of higher daytime demand. The early-morning peak in generation corresponds with low loads in all seasons. Mismatches in the timing of Great Lakes wind electricity generation and load will require storage to manage a high penetration of energy; however, this assessment could be affected by changes in demand patterns and the mix of generation resources in the region. System operators around the Great Lakes predict that greater electrification—primarily of building heating, vehicles, and industrial processes—could shift peak loads from summer to winter by 2040, which would align with the peak wind season (Midcontinent Independent System Operator [MISO] 2021; New York Independent System Operator [NYISO] 2022; PJM 2022). Hourly load patterns could also experience changes such as summer loads peaking later in the day (NYISO 2022) and the development of early-morning peaks in the winter and spring (MISO 2021).

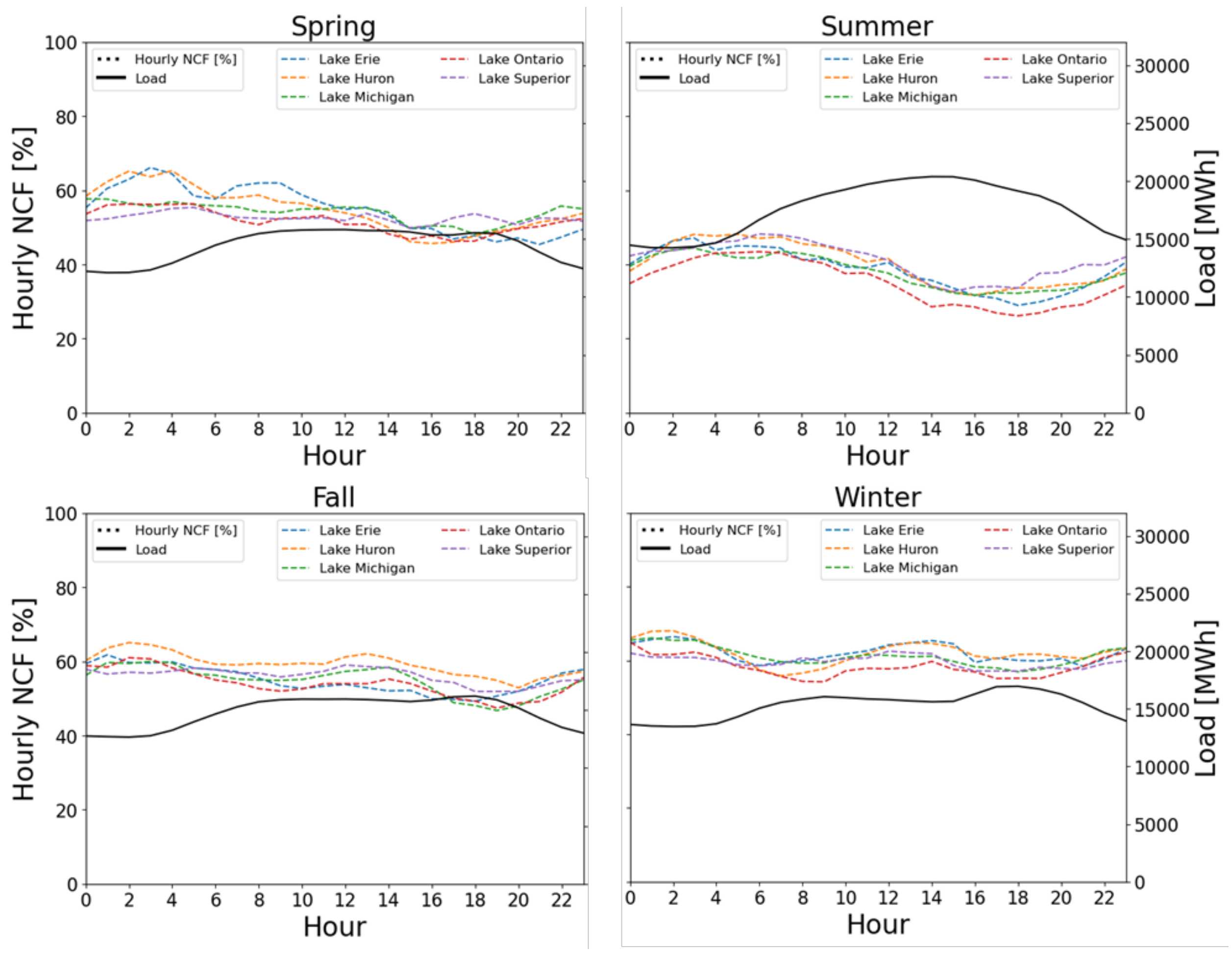

Figure 5. Hourly generation and load in the Great Lakes region.

Generation profiles use wind speed data from March 2019 to February 2020, averaged across seasons as follows: spring (MAM), summer (JJA), fall (SON), and winter (DJF). The coordinates of the wind data in each lake are Lake Erie (41.73N, 82.06W), Lake Huron (44.15N, 83.24W), Lake Michigan (42.25N, 87.46W), Lake Ontario (43.61N, 76.62W), and Lake Superior (46.75N, 87.29W). Loads are an average of modeled busbar electrical demand in 2030 for New York, Ohio, Michigan, Illinois, and Wisconsin.

3.1.3 Lakebed

Characteristics of the lakebed that are relevant to offshore wind energy development include the water depth, lakebed slope, depth to bedrock, and sediment parameters, such as shear strength and chemical composition. Water depth is the main selection criterion for fixed vs. floating substructures. Slope, depth to bedrock, and shear strength all influence the choice of suitable anchors and foundation designs. Shallow bedrock and soft lakebed soils limit practical options for substructures in the Great Lakes, especially for fixed-bottom wind turbines. Monopiles, which are the most widely used type of fixed-bottom foundation, may not be feasible due to the low-shear-strength soils that are common in the Great Lakes. The selection of vessels for installation and maintenance activities is also influenced by water depth and lakebed slope. Historically, certain industrial activities along the shores of the Great Lakes and their tributary rivers have deposited heavy metals and toxic chemicals in layers of sediments that could potentially be disturbed when installing wind turbine substructures and intra-array and export cables. Understanding the location and concentration of these contaminated soils is necessary to avoid introducing hazardous levels of contaminants into water supplies.

Water Depth (Bathymetry)

The National Oceanic and Atmospheric Administration (NOAA) has compiled digital and historical sounding data covering the geology and bathymetry of the Great Lakes (National Centers for Environmental Information undated). Bathymetric data are available for Lake Ontario, Lake Erie, and Lake Huron at a contour interval of 1 m, and for Lake Michigan at a 5-m contour interval. Bathymetric contours for Lake Superior were not completed, but data are available at a (horizontal) resolution of approximately 90 m. Bathymetry of the Great Lakes is shown in Figure 6. The area of the Great Lakes within the United States is 156,000 km^2; nearly 60% of that area (91,000 km^2) has water depths of at least 60 m, which is the approximate depth at which floating substructures become more cost-effective than fixed-bottom foundations (red line in Figure 6). Lake Superior has the deepest water, whereas Lake Erie water depths are 60 m or less.

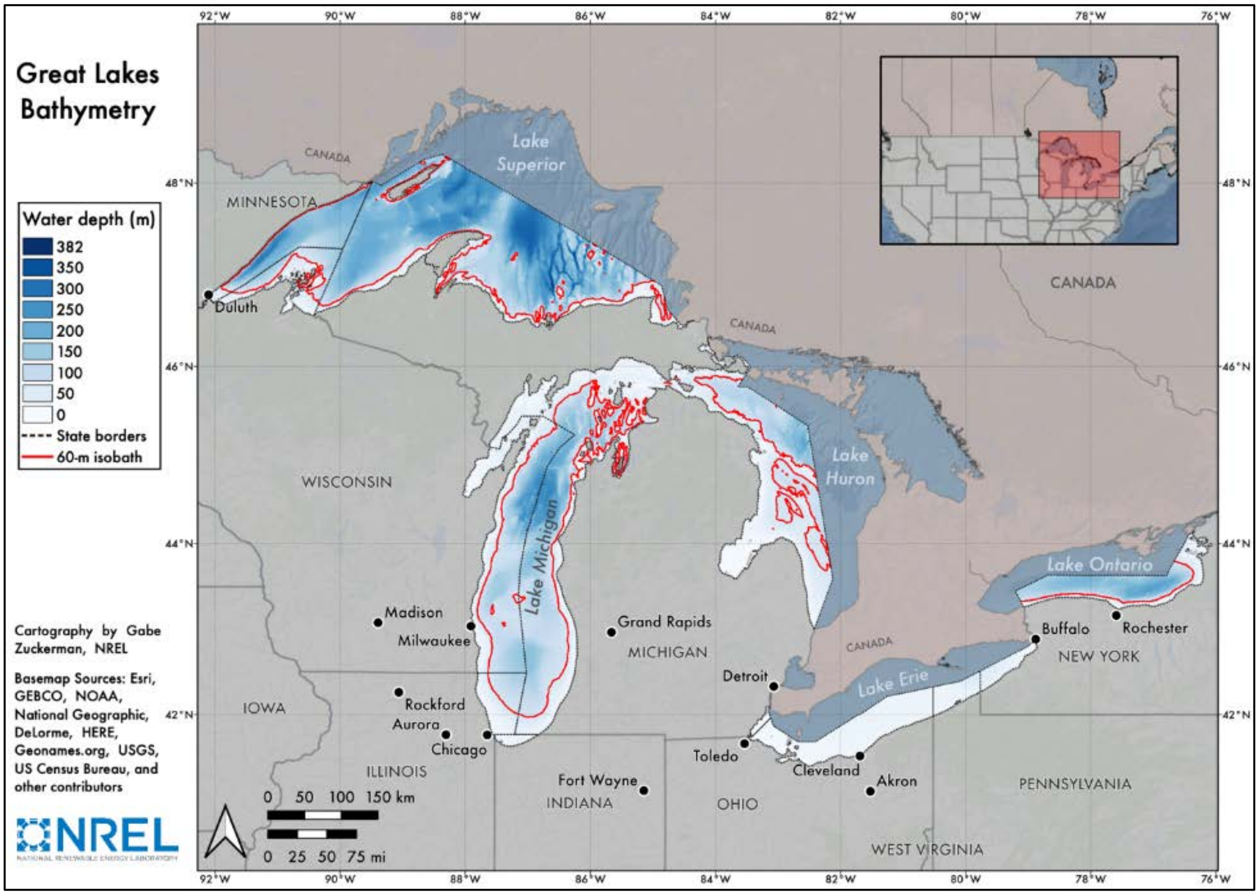

Figure 6. Water depths in the U.S. Great Lakes shown with the 60-m isobath (nominal depth limit for fixed-bottom offshore wind structures)

Sediment Characterization

The Great Lakes Sediment Archive Database (Environment and Climate Change Canada undated), Great Lakes Sediment Monitoring and Surveillance Database (Government of Canada and Environment and Climate Change Canada 2015) and Great Lakes Aquatic Habitat Framework (undated) each provide data for classifying sediments across the Great Lakes.[7] The classification schemes use different nomenclature and methodologies, resulting in contrasting descriptions of the sediment at a given location depending on which data set is used. The Canadian data include measurements of the chemical composition and grain size of sediments, whereas the Great Lakes Aquatic Habitat Framework data contain descriptions of the lakebed sediments from various peer-reviewed publications. Neither source provides measurements of shear strength or depth to bedrock. Site-specific geotechnical surveys that are typically part of the wind power plant development process will provide information about soil strength; however, preliminary studies of lakebed soil characteristics could inform the development of substructure or anchoring solutions that are tailored to common soil types in the Great Lakes.

[7] Data from the Great Lakes Sediment Monitoring and Surveillance Database do not include Lake Michigan.

Concentrations of heavy metals and industrial chemicals entering the Great Lakes peaked in the 1960s and 1970s, before regulations were enacted to protect water quality. Many of these contaminants sank out of the water column and now reside in lakebed sediments. Levels of these substances in surficial sediments (the top 1−3 centimeters) have broadly been declining since that period (U.S. Environmental Protection Agency [EPA] and Environment and Climate Change Canada 2022). The distribution of contaminants and rate of sedimentation varies across the lakes, which means that contaminated sediments may be found at different depths below the surface of the lakebed, on the order of a few centimeters to a few decimeters. Installing wind turbine foundations, anchors, and power cables would require disturbing the soil at and below these depths. The U.S. Army Corps of Engineers' Great Lakes Dredging Team[8] provides information regarding best practices for managing sediments that are disturbed or removed from the lakebed. These recommendations are based on extensive experience: the U.S. Army Corps of Engineers removes between 1.5 and 4 million cubic meters of sediment annually from Great Lakes harbors and channels, half of which is considered too contaminated for open lake disposal (U.S. Army Corps of Engineers 2012).

3.1.4 Waves and Currents

Measurements of wave height and period are collected by several buoys in the Great Lakes, and the data are available from NOAA's National Data Buoy Center for three seasons (NOAA 2021). Buoys are taken in during the winter. The Great Lakes Coastal Forecasting System[9] provides wave forecasts that are updated four times daily. The peak season for large waves in the Great Lakes is late fall, when storms can generate significant wave heights[10] close to 7 m (NOAA 2021). During the winter and early spring, wave formation is inhibited by ice cover (if present). Average significant wave heights in the late spring and summer months are 0.5 m or less. As a result, the mild summer wave climate could be advantageous for installation activities. The observed extreme wave heights are comparable to Atlantic offshore wind sites, where maximum significant wave heights are between 5 and 10 m (Barthelmie et al. 2021). Observations are needed to understand the winter wave climate.

Currents in the Great Lakes have mean velocities between 0.015 and 0.03 m/s (Bai et al. 2013). In the winter, currents are primarily driven by the wind. In the summer, currents are also driven by differences in density between warmer and cooler areas within the lakes. The relatively low velocities of currents in the Great Lakes generally result in low sediment transport and are unlikely to demand specialized design adaptations. However, understanding the currents near potential wind energy areas will enable modeling of scour around foundations and the fate of suspended sediments and contaminants.

3.1.5 Ice

Each of the Great Lakes has areas of seasonal ice cover, with a high degree of variability in ice cover area between them (Figure 7). Lake Erie freezes most often, with an average annual maximum of 82% ice cover since 1973, followed in declining order by Lake Huron, Lake Superior, Lake Michigan, and Lake Ontario, which averaged 30% maximum ice cover annually.

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[8] https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Dredging-Team/
[9] https://www.glerl.noaa.gov/emf/waves/WW3/
[10] The significant wave height is the average of the highest one-third of waves over a period.

There is also significant year-to-year (Bai et al. 2012) and decadal variability in ice cover (Wang et al. 2018b). Because there is less of a temperature gradient from the poles to the midlatitudes in the face of global warming, the stability of the jet stream has weakened and could lead to more frequent extreme weather in the midlatitudes (Screen and Simmonds 2014), bringing with it times of variable ice cover in the Great Lakes. Since 1973, the annual maximum frozen area over all the lakes has ranged from nearly 95% to less than 12%, with a long-term average annual maximum of 53% ice coverage (Great Lakes Environmental Research Laboratory [GLERL] undated). Ice cover duration has been declining with both Lake Ontario and Lake Superior losing almost 1 day of ice cover per year since 1973 (Figure 8). Although there is a general trend of declining ice area in the Great Lakes, Lake Superior is the only lake with a statistically significant decline (Wang et al. 2012; Wang et al. 2018a).

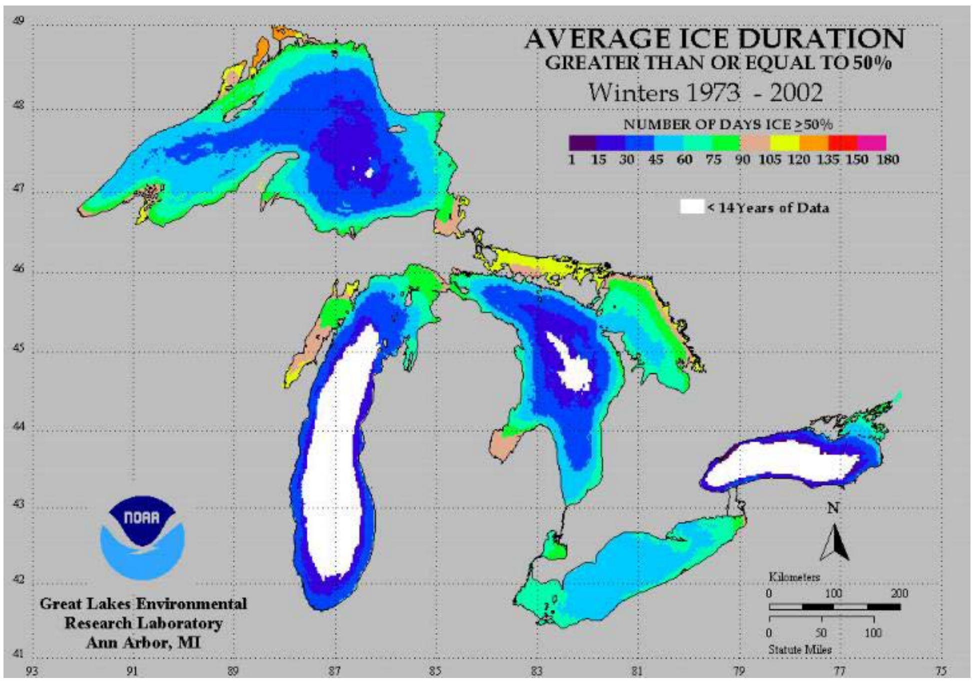


Figure 7. Great Lakes annual ice cover duration. ***Figure from GLERL (2022a)***

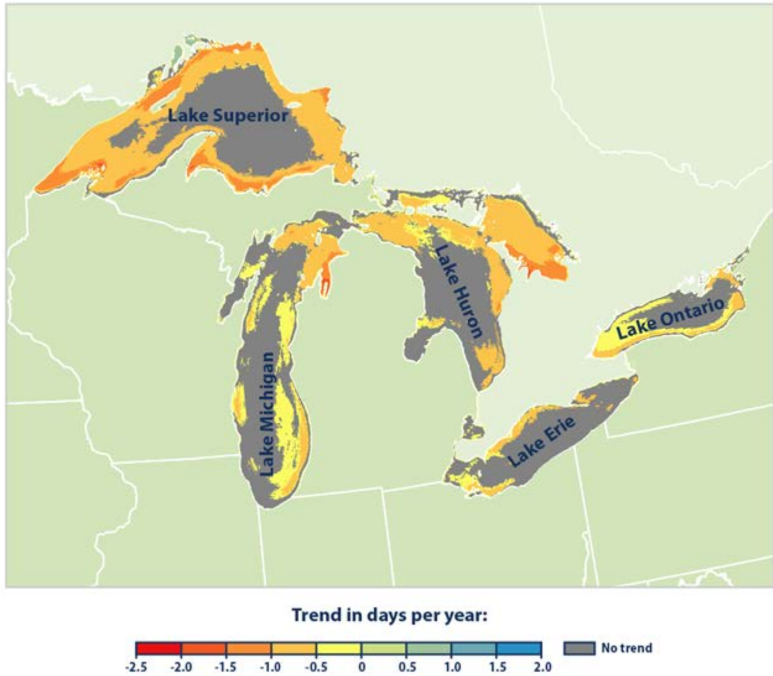


Figure 8. Trend in duration of ice cover from 1973 to 2019. ***Image from EPA (2022a)***

Predicting ice cover is important for minimizing impacts on a range of activities such as commercial shipping, fishing, and hydropower generation (EPA 2022a). Several key variables related to surface ice are already being forecasted on the Great Lakes. The Great Lakes Coastal Forecasting System uses atmospheric observations and forecasts in a physical modeling framework to predict wave height and period, currents, water temperature, and ice concentration. These variables are forecast in real time, 1 to 3 days in advance by GLERL. Ice thickness, ice velocity, and vessel icing are also available for up to 5 days but need further development to be approved for operational use. There are also experimental projections of seasonal ice cover at GLERL using statistical regression models (Bai et al. 20212; Wang et al. 2018a). Hindcasts and longer-term projections have recently been modeled by coupling a regional climate model with a three-dimensional lake model (Great Lakes-Atmosphere Regional Model), instead of using the more common one-dimensional lake column or simply neglecting coupled atmosphere lake interaction (Xue et al. 2022). Data collection of ice concentration and thickness could also come from the U.S. Coast Guard, which operates icebreaker ships on the Great Lakes.

Ice ridges are possibly the least well-understood features of surface ice in the Great Lakes but may pose the highest risk to offshore wind structures and power cables. Ice in the water can also impede repair and cleanup efforts, as was the case when oil used for electrical insulation of a transmission line leaked in 2018 under the Straits of Mackinac (Bergquist 2018). Ridges form when floating ice sheets collide, and chunks of ice accumulate above and below the waterline (keels) along the edges where the sheets intersect. The rubble can then freeze together into a mass that is much taller and deeper than the original flat sheets. The first satellite-based evidence of ice ridges in Lake Erie were observed using synthetic aperture radar surveys in a comprehensive study of Lake Erie ice cover (Daly 2016). Collisions between ice ridges and wind turbine substructures would involve a larger cross-sectional area and likely produce more extreme loading than level ice (Croasdale and Allyn 2018). Power cables are also at risk of damage from ice ridges that scour the lakebed as they approach the shoreline. There have been some direct observations of ice ridges in the Great Lakes as well as indirect evidence of scouring on the lakebed where ice ridges travel from deeper to shallower water (Titze and Austin 2016; Hawley et al. 2018). The frequency and spatial distribution of ice ridges have not been studied in detail.

3.2 Key Challenges

3.2.1 Characterize Surface Ice Extremes

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. Structures installed in the Great Lakes must be designed to withstand interactions with ice that forms and drifts across the lake surface. The extent and timing of ice cover is monitored using satellite imagery, which provides several decades of historical data. However, further research is needed to characterize design drivers, such as ice pressure, likelihood of ice presence in the longer term, ice-wave interactions, snow cover on ice, and coupling with river runoff (e.g., Bai et al. 2020). Understanding freshwater ice strength, velocity, and its interaction with analogous structures (e.g., bridges), also requires more work. Notably, offshore structures built in the ocean are not designed with freshwater ice properties in mind, but rather sea ice. Transferring these designs directly to freshwater structures would be problematic because freshwater ice is very different than sea ice. For example, sea ice is much softer (Weeks and Ackley 1986) and requires thicker ice to carry the same load as freshwater ice. However, structures have been built to withstand freshwater ice, such as the bridges in the Great Lakes, or notably, the Confederation Bridge in Canada. Some freshwater ice loading research has been done (Pei et al. 2017), including on how ice action against bridges may change under a warming climate (Barrette et al. 2017). More research is necessary to understand how to design floating and fixed-bottom wind turbines to withstand hard freshwater ice and ice ridges/keels.

Consequences and impact. Addressing this challenge area would pave the way for better engineering of wind energy structures and service vessels to interact with freshwater ice in the Great Lakes. Design decisions depend on how well ice characteristics can be predicted, including ice presence and thickness. In the most extreme case, underestimating ice loads could result in the destruction of a support structure or vessel. Conversely, overestimating ice loads to account for the high uncertainty could lead to overdesigned structures that are more costly to build and install. Robust modeling and characterization of surface ice will provide accurate inputs to the design process.

Recommended research activities include:

- Expanding model development and validation for ice-wave and ice-ice interactions (including ridges) for freshwater ice (level of effort: $1–$2 million, timeline: 1–2 years)
- Assessing the likelihood of ice cover on a geospatial basis including developing longer-term ice cover models and scenarios (level of effort: $500,000–$1 million, timeline: 6 months–1 year)

- Characterizing snow cover on the Great Lakes including modeling and validation to understand effects on loading and overflow on top of the ice (level of effort: $1–$2 million, timeline: 1−3 years)
- Characterizing impacts of climate change on ice cover and likelihood of extreme-ice winters and quantifying these impacts on the design basis for the wind turbines and how O&M might be affected (level of effort: $500,000–$1 million, timeline: 6 months–1 year)
- Conducting a multiyear field campaign to measure ice ridges, their formation, strength, bearing capacity, thickness, and locations in each lake (level of effort: >$2 million, timeline: 3−5 years).
- Explore state-of-the-art, physics-based models for predicting ice ridges and other patterns of ice formation using weather modeling information and techniques. (level of effort: $1–$2 million, timeline: 1−3 years).

3.2.2 Characterize Ice Formation From Spray

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. Wind and wave action can introduce water droplets into the air above the surface of the lakes. In cold temperatures, these droplets may freeze on contact with exposed surfaces on a wind turbine or substructure. Ice accumulation on the tower and substructure of a wind turbine add weight and excess—possibly asymmetric—loads that the structures must be designed to withstand. Ice spray accumulation at higher elevations could reduce energy production by degrading the blades' aerodynamics and, as more ice builds up, produce high loads and force wind turbines to shut down. It is not known to what degree this could be a problem. Mitigation measures for wind turbines in cold climates include anti-ice coatings and heating systems (International Energy Agency 2018). These systems have not been tested in freshwater spray conditions.

Ocean-based wind turbines are exposed to more airborne water droplets than land-based turbines, but the presence of salt in the droplets lowers the freezing point and results in softer ice. As a result, characterizing the freshwater spray environment is needed to design appropriate substructures and ice mitigation systems for Great Lakes wind turbines. Existing structures such as lighthouses and bridges provide a starting point for gathering information about ice accumulation. However, Great Lakes wind energy development may occur farther from shore than these structures are typically located—and therefore exposed to—different conditions. The impacts could be greatest on the unfrozen lakes when the air temperature is below freezing.

Consequences and impact. An excess of ice accumulation can reduce energy production and increase structural loading on wind turbines. Future research could characterize ice accumulation on wind turbine and analogous surfaces under freshwater spray conditions and investigate the effectiveness of existing and novel mitigation strategies. Research in this area could help lessen ice buildup on offshore wind infrastructure and provide the necessary information to avoid possible catastrophic loading and performance loss.

Recommended research activities include:

- Surveying existing ice formation data sets from structures on and around the lakes (level of effort: <$200,000, timeline: <6 months)
- Deploying winterized meteorological-ocean-sensing buoys/meteorological masts with additional capabilities to measure ice accumulation and/or airborne droplet concentration (level of effort: >$2 million, timeline: 3−5 years)
- Developing mitigation strategies for ice formation on Great Lakes wind turbines (level of effort: $200,000−$500,000, timeline: 1−3 years).

3.2.3 Characterize and Validate Wind Resource

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
3	No	No	Yes	Medium

Description. The quality of the wind resource is key to determining the economic viability of a wind energy project. Assessments of the Great Lakes wind resource rely primarily on atmospheric modeling and wind speed measurements at levels much lower than typical wind turbine hub heights. Wind speed measurements at hub height could be used to validate modeled results or identify phenomena that are not captured by current models. Areas for study include the variation of wind speed with height and over time. Both wind speed and demand for electricity exhibit daily and seasonal patterns. The value of wind energy may be higher when periods of energy production coincide with periods of high demand that are not met by other generation sources (see Section 6.2.1 for recommended research activities related to grid integration).

Consequences and impact. Better characterization of the wind resource enables improved site selection and lowers the risk that wind power plants will underperform. Without action, energy production could be lower than predicted, wind turbines could be poorly matched to site characteristics, and the need for energy storage or other generation sources could be over- or underestimated. In addition, there is significant uncertainty in modeled resource data, and validation from observations is necessary for all resource data.

Recommended research activities include:

- Deploying buoys equipped with lidar devices to validate modeled wind speed and direction up to approximately 300 m. Ideally, this would encompass at least a year of field data collection at multiple sites on the Great Lakes. Deployment of buoys through the winter season would require design adaptations to protect against ice or selection of sites with low probability of ice cover and contingency plans to remove buoys if needed. (level of effort: $1–2 million, timeline: 1−3 years)
- Developing forecasting tools specific to the Great Lakes wind resource for short and long timescales (level of effort: >$2 million, timeline: >5 years)
- Reviewing scientific literature analyzing the effects of climate change and cumulative wind energy deployment on wind resource projections and assessing the potential

economic impacts on Great Lakes wind energy (level of effort: $200,000–$500,000, timeline: 6 months–1 year).

3.2.4 Characterize Lakebed and Sediments

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
3	No	No	Yes	Medium

Description. Shallow bedrock and soft lakebed soils limit the options for feasible substructures in the Great Lakes, especially for fixed-bottom wind turbines. Monopiles, which are the most widely used type of fixed-bottom foundation, must be driven into the lakebed to a depth of 20 m or more, and the required depth increases for low-shear-strength soils that are common in the Great Lakes. The size and type of anchors for floating wind turbines are also affected by soil conditions. In addition, water depth and lakebed slope affect the choice of suitable substructures for offshore wind, including the cost of design and installation, and choosing which vessels are suitable for certain offshore tasks. New surveys of the lakebed could take advantage of improvements in measurement techniques to gather multibeam data, sub-bottom profiles, and thermal conductivity data.

Consequences and impact. Better characterization of the lakebed lowers the risk that preconstruction surveys will encounter shallow bedrock or other challenges that could increase the cost of substructure design or deter development in the surveyed location. If lakebed terrain is more complex than anticipated, project costs could increase because cabling may need to be rerouted, more cable may be required, and cable and mooring installation could face challenges. Increasing the level of knowledge about the lakebed prior to leasing would increase the value of the lease areas.

Recommended research activities include:

- Surveying published literature and data repositories to summarize existing knowledge of the physical and chemical properties of the lakebed and sediments and identify focus areas for future work (level of effort: <6 months, timeline: <$200,000)
- Identifying high-priority areas for offshore wind development and conducting geophysical and geotechnical surveys. The level of effort assumes a single area of focus and would increase with additional areas (level of effort: >$2 million, timeline: 1−3 years).

3.2.5 Characterize Waves and Water Currents

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
3	No	No	Yes	Medium

Description. Wave-induced loads must be considered in the design of wind turbine substructures for the Great Lakes. Existing wave measurements could be supplemented by data from buoys as described under Section 3.2.3. Water currents contribute to the motion of sediment and ice through the lakes. As a result, installing substructures, anchors, and electrical cables will require disturbing the lakebed and resuspending sediments that may potentially be contaminated with heavy metals and chemicals from lakeside industries. Characterizing water currents at installation sites during the summer construction season could predict where any disturbed sediment is likely to be transported. After installation, currents may determine where scouring is likely to affect wind turbine foundations, anchors, and power cables. There is particularly a lack of knowledge related to the near-bottom currents that directly affect the seabed and scour around wind turbine components.

Consequences and impact. Understanding currents, especially near the lakebed, that flow around wind energy development sites enables more accurate prediction of sediment transport and scour processes. Informed predictions of these processes will help with planning any mitigation measures that may be needed to protect drinking water supplies and avoid costly reburial of cables exposed by scour.

Recommended research activities include:

- Modeling sediment transport associated with substructure and cable installation processes (level of effort: $200,000–$500,000, timeline: 1–3 years)
- Identifying where strong currents are typically located (e.g., river mouths, areas particularly affected by wind, or steep topography) (level of effort: <6 months, timeline: <$200,000)
- Characterizing impacts of climate change on the size and frequency of extreme waves and quantifying their effects on the wind turbine design basis and O&M activities (level of effort: $500,000–$1 million, timeline: 1−3 years).

4 Infrastructure

Offshore wind energy development requires proper infrastructure, which comprises the physical and organizational structures and facilities used for construction and operations. Conventional offshore wind infrastructure primarily includes component manufacturing facilities; methods of transporting components; port facilities and equipment for component assembly; and vessels and methods used for installation, operation, and maintenance of the system. Manufacturing facilities must be able to produce large-scale components like wind turbine towers, turbine blades, and substructures. These facilities would ideally be co-located at port, but otherwise, methods of transporting the technology components to port from either domestic or international sources are required, such as by highway, rail, or water. The ports need to be large enough to support the assembly operations of these components, which means having enough quayside space for storage and assembly, proper soil-bearing capacity, and large cranes. Once assembled, large vessels are typically used to carry or tow the wind turbine system to the site for installation. Deficiencies in any part of the infrastructure or supply chain can drastically impact the cost and timeline of an offshore wind energy project.

Various types of specialized vessels are used to support the transportation, installation, operations, and maintenance procedures of offshore wind turbines, substructures, substations, and cables for either fixed-bottom or floating offshore wind energy projects. The availability of vessels can determine the types and sizes of technologies to be used based on their installation method, which can affect the requirements of the necessary port and infrastructure systems. Figure 9 depicts a common WTIV used for offshore wind energy development to assemble the turbine blades.

Figure 9. Example installation vessel used for offshore wind energy development. ***Photo by Lyfted Media for Dominion Energy***

Wind turbine and substructure assembly and installation are the most important processes in wind power plant development. For fixed-bottom systems, the substructure and turbine are transported out to the site and installed with a heavy-lift vessel. For floating systems, the substructure and turbine are assembled and commissioned at port and towed out to the site for installation.

The different types of ports can be classified according to their needed function, such as:

- Turbine assembly and installation
- O&M
- Substructure fabrication
- Manufacturing supply chain.

Assembly and installation ports present the biggest challenge because they have the most stringent requirements for crane capacities and heights, lay down or quayside space, port depth, wharf length, and overhead air draft limits to allow assembled wind turbines and substructures to be towed out to site. O&M ports have similar requirements as the assembly (marshalling) ports but do not require as much space. The substructure fabrication ports do not have the same constraints for high-capacity overhead lifting and air draft but should be close to or part of the assembly port, with the ability to maneuver the substructures, which are the heaviest components. Manufacturing and supply chain port facilities for other components, such as wind turbine towers and nacelles, can be located on the lakes within reasonable distances for shipping. Figure 10 shows a graphic of an offshore wind energy port and some of its requirements, such as adequate laydown space, wharf length, crane capacities, and water depths. These requirements may vary depending on if the port is supporting fixed-bottom or floating wind turbine development, but the requirements will depend on what technology is used. Typically, floating ports require more area because more construction and assembly activities are done at the port. These space requirements could change significantly if new float-out designs are adapted for the Great Lakes.

Figure 10. An example schematic of an offshore wind energy port supporting floating wind turbine energy development. ***Graphic by Besiki Kazaishvili, NREL***

4.1 Current Situation

Existing infrastructure is probably not capable of supporting Great Lakes wind energy development using 15-MW wind turbines, which makes costs higher in the near term, but momentum in Great Lakes project development would likely drive progress in Great Lakes infrastructure, which would lower costs. One limitation of the Great Lakes infrastructure is that large WTIVs or heavy-lift vessels, typically used for installation of fixed-bottom wind turbines, cannot be brought into the lakes due to width and draft constraints through the locks of the St. Lawrence River. These large vessels do not currently exist in the Great Lakes. Ships that do exist primarily consist of large cargo freighters that transport various bulk items like iron ore or coal throughout the lakes, as well as oil tankers, tugboats, barges (Figure 11), and ferries (Shipwatcher News undated).

Figure 11. Example of a Great Lakes tug and barge. ***Photo by Peter J Markham***

The St. Lawrence Seaway, which flows from the Great Lakes to the Atlantic Ocean, includes seven locks in the St. Lawrence River and eight locks in the Welland Canal (the canal that connects Lake Erie to Lake Ontario) that limit the size of vessels that can travel through the Seaway system. The maximum beam, or width, of a vessel that can navigate the locks is 23.8 m and the maximum air draft is 35.5 m (Great Lakes St. Lawrence Seaway Development Corporation 2022). Some smaller jack-up vessels could navigate the locks into the lakes for system installations, but their reduced capacity to fit through the locks would limit the size of wind turbines they could install to about 4- to 5-MW turbines (Douglas-Westwood LLC 2013).

The Jones Act requires any vessel transporting goods from one U.S. port to another to be built, registered, owned, and crewed by U.S. citizens. Therefore, in the Great Lakes, only U.S.-flagged vessels can be used to bring components from U.S. ports to wind turbine sites, but there are other options that can be used. For example, many offshore wind energy projects on the Atlantic coast plan to use U.S.-flagged feeder barges to shuttle turbines and components from U.S. port facilities to foreign-flagged WTIVs stationed at the wind farm that will install the wind turbine nacelles.

The most likely scenarios for vessel acquisition for Great Lakes wind energy are:

- Altering existing Great Lakes vessels (e.g., crane barges for installation)
- Building custom vessels specifically for Great Lakes wind energy development
- Designing the Great Lakes wind energy technology and installation methods to avoid using large vessels

- Physically reworking existing, ocean-going vessels to be transported to the Great Lakes and then reconstructing them at the Great Lakes ports.

With careful engineering, the existing vessels on the Great Lakes have the potential to be redesigned to support wind energy development in this region, likely using combinations of local barges retrofitted with large, land-based cranes. New technologies can be used in conjunction with retrofitted Great Lakes vessels to overcome engineering barriers, such as self-installing technologies to avoid large crane height requirements (Knauber 2022; Wåsjø et al. 2013). Otherwise, certain wind turbine or substructure technologies would require custom vessels to be built specifically for Great Lakes wind development, with possible support from the Inflation Reduction Act for the domestic production of specialized offshore wind installation vessels (Center for American Progress 2022). The Great Lakes have well-established shipyards capable of building some vessels suitable for offshore wind energy development, such as service operation vessels and possibly larger vessels as well (Blenkey 2023).

To avoid the need for WTIVs or heavy-lift vessels, fixed-bottom and floating system technologies would have to be assembled at port, and then towed to site using smaller vessels, like tugboats. Otherwise, developers with fixed-bottom or floating technologies that require specialized installation vessels could consider creative solutions to obtain the proper installation vessels in the Great Lakes, such as physically altering them at an ocean-based shipyard to fit through the locks and then reconstructing them at Great Lakes ports. For example, a 1,000-foot freighter had its bow and stern sections built in Pascagoula, Mississippi, and then joined together to sail through the locks where they were then dismantled in the Great Lakes to attach to the two ends of the midsection of the freighter built in Erie, Pennsylvania (Sundstrom 1972).

Currently, the Great Lakes have many established ports for various industries (Figure 12). A detailed analysis has not yet been done, but it is likely that many ports could support future wind energy development, but all would require some level of upgrade. Optimally, a port should not only be able to accommodate the cost and scope of upgrades, but also have proximity to the expected sites and the willingness of the port facility management to accommodate this new industry. For floating wind systems, the substructure fabrication port requirements would be about the same for Great Lakes wind energy projects as for ocean-based floating offshore wind energy projects. For fixed-bottom wind systems, the substructure fabrication ports may need to be adapted more for new designs that float out to overcome potential installation barriers, such as the lack of installation vessels in the lakes, but the port adaptation requirements for alternative substructure designs are very technology-specific and have not yet been defined.

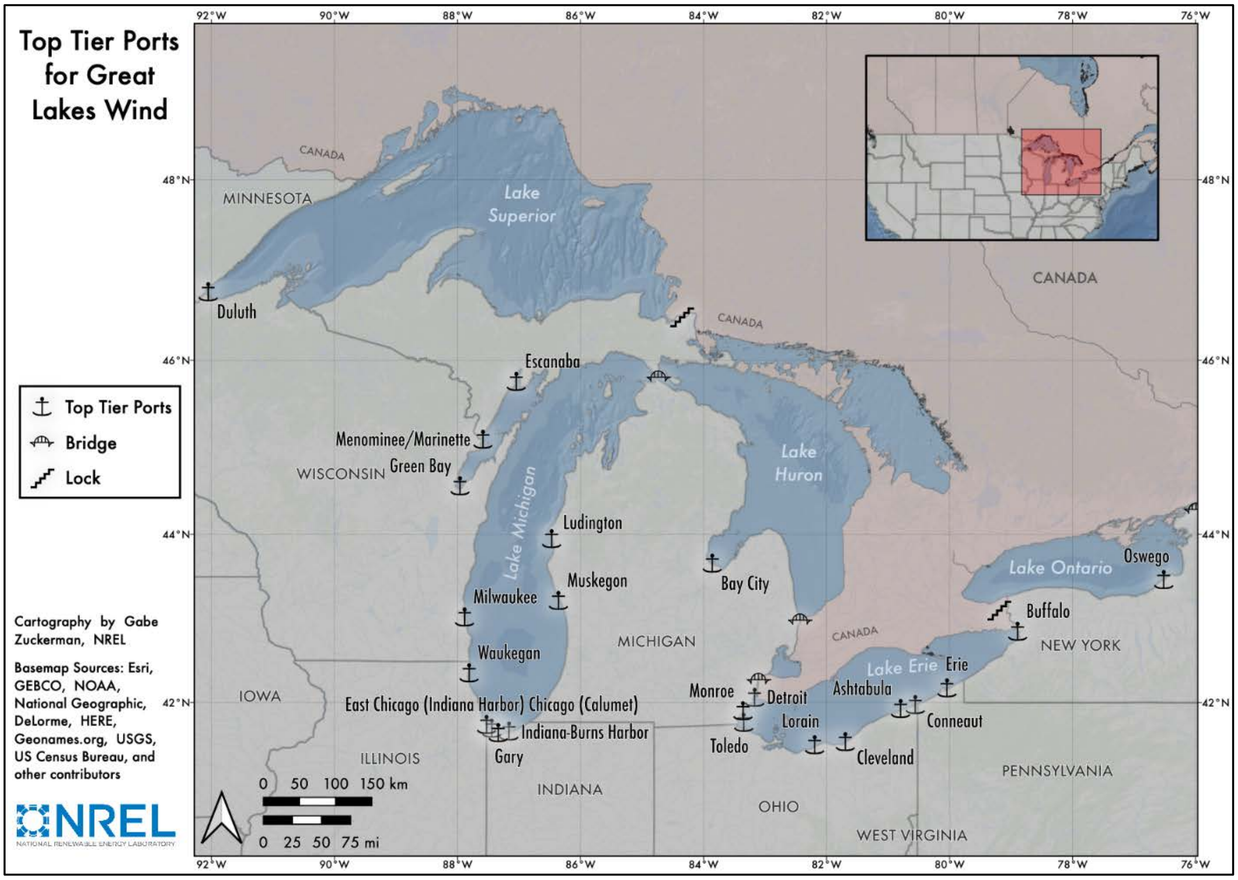


Figure 12. Possible ports for Great Lakes wind energy development. ***Image from NREL***

There are many ports on Lake Erie and Lake Michigan near major cities and load centers that could potentially support fixed-bottom and floating offshore wind projects, respectively. The ports of Buffalo, Cleveland, and Toledo on Lake Erie, and the ports of Indiana-Burns Harbor, Calumet (Chicago), and Milwaukee are well-established, with large harbors and feasible options for significant lay down space that can potentially be upgraded to support component assembly and installation operations. By comparison, Lake Ontario, Lake Huron, and Lake Superior each only have one major U.S. port that would be most suited to support wind plant port operations. If larger ports supporting Great Lakes wind energy become congested with competing markets, there are many smaller ones not included in Figure 12 that could potentially be upgraded for use as manufacturing ports in the Great Lakes wind energy supply chain.

The existing supply chain that has traditionally supported other heavy industry in the region may be able to provide a solid foundation for new offshore wind supply chains to build from. Figure 13 shows a cargo vessel being used to transport land-based wind turbine blades to port.

Figure 13. A freighter transporting wind turbine components to port. ***Photo by Siemens Press Picture***

Currently, some Great Lakes wind energy components can likely be procured using existing Great Lakes supply chains. Wind turbine blades are being unloaded at Port Fisher in Bay City, Michigan, and turbine towers are being handled by the Port of Monroe, located between Detroit, Michigan, and Toledo, Ohio, on Lake Erie, for land-based wind energy projects (French 2020; Eagle undated). For larger wind energy components, until new factories are built or converted, components would have to be sourced by more mature land-based and offshore wind supply chains domestically or internationally. There are numerous manufacturing facilities throughout the Midwest and Northeast that may be suitable for upgrades to fabricate and transport the components required for large-scale development. These components could then either be shipped on vessels that can pass through the locks, or transported through other methods, such as inland waterways like the Chicago River or highways and railroads. Currently, there should not be any major limiting factors to transport large-scale wind turbine components (e.g., blades, towers, nacelles) to the Great Lakes, other than the transportation vessel size through the locks and the locations and capacities of manufacturing facilities. Once at port, Great Lakes vessels can be used to distribute the wind turbine components to other ports on other lakes, if they are able to pass through other locks or under bridges between lakes.

This infrastructure assessment assumes use of only American infrastructure. Ontario is the only province that borders all Canadian sections of the Great Lakes. The province imposed a moratorium on Great Lakes wind energy in February of 2011 (Taylor 2011). Prior to the moratorium, there were at least two Canadian Great Lakes wind energy projects under development. Canadian infrastructure may exist that could potentially increase the viable options for Great Lakes wind energy. For example, an existing Canadian or foreign-flagged vessel (small enough to enter the lakes) could travel between a Canadian port and a U.S. Great-Lakes-based wind energy site without violating the Jones Act.

4.2 Key Challenges

The following lists a set of the most important, high-level challenges to Great Lakes wind energy infrastructure that would need to be addressed with further research.

4.2.1 Assess Vessel Requirements and Solutions

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. Some of the vessels that are needed for various aspects of offshore wind energy development, such as wind turbine and substructure installation, cable laying, or O&M, may not be able to navigate the locks of the St. Lawrence Seaway. This inaccessibility creates the need to find alternative solutions for installation vessels in the Great Lakes. These solutions may include retrofitting existing Great Lakes vessels, building new vessels specifically for this region, developing alternative technologies and installation solutions that avoid using large vessels, or considering creative solutions to transport existing vessels to the Great Lakes. Over time, new technologies like self-installing methods might be able to provide solutions to reduce vessel requirements, but a full assessment of these alternatives is needed. Once assessed, proposed vessels for Great Lakes wind energy development will have to meet port requirements and vice versa. The biggest challenges are likely to be vessel draft limits and overhead air-draft clearances.

Consequences and impact. Without capable vessels or custom Great Lake installation solutions, essential Great Lakes wind energy development and operations will be limited and costly. As a result, viable installation methods need to be developed for new technology types that avoid these constraints. Similarly, methods are still needed for properly burying export and array cables with the available fleet. Without development of these methods, the risk posed by ice to the electric infrastructure may be unacceptable. The availability of technology-compatible vessels is essential to the deployment of Great Lakes wind energy and especially the 15-MW-class wind turbines, which would allow access to maturing industrialized supply chains on the Atlantic and significantly lower costs. The resolution of this challenge is imperative for Great Lakes wind energy development.

Recommended research activities include:

- Surveying the types of vessels available in the Great Lakes and assessing their upgrade potential to support Great Lakes wind energy development for specific activities and assessing the critical needs for vessels that do not exist in the Great Lakes (level of effort: <$200,000, timeline: <6 months)
- Developing novel designs to retrofit existing regional vessels to support Great Lakes wind energy, such as installation vessels using existing, regional barges and cranes, creative cable-laying vessel solutions, or new self-installing technologies to avoid conventional vessel requirements (level of effort: >$2 million, timeline: 3−5 years)
- Issuing a competitive ship design and cost analysis Funding Opportunity Announcement for custom-built Great Lakes wind energy vessels that are needed for technologies that cannot be avoided through alternative designs and installation methods for fixed-bottom and floating offshore wind. Designs may include vessels that can navigate the locks of the St. Lawrence Seaway or ships built in the Great Lakes (level of effort: >$2 million, timeline: 3−5 years).

- Developing integrated supply chain solutions to adapt vessels, substructure designs, ports, and manufacturing to the Great Lakes region to industrialize Great-Lakes-based technology (level of effort: $3,000,000–$5,000,000, timeline: 2−3 years).

4.2.2 Assess Port Capacities and Solutions

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. In parallel with the vessels challenge, the capacity of the ports is crucial for Great Lakes wind energy development. Ports are needed for the manufacturing, assembly, and installation activities of a wind turbine system. Ideally, ports should be close to the wind plant site to reduce transportation costs and downtime. They should also be capable of supporting the vessels used in offshore wind farm operations in terms of port depths and overhead clearances. There are currently no ports on the Great Lakes that have been identified that can currently support large-scale development, and it is likely that existing ports would need significant upgrades. To better understand the needs, assessments should include port lay down or quayside space and expansion capabilities, soil-bearing capacities, available crane capacities, air-draft limits like bridges or powerlines, port management, and other barriers limiting Great Lakes wind energy supply chain development or access to global supply chains. This can be done for large or small existing ports, where small ports could provide hidden benefits such as reduced vessel traffic or larger dock spaces. In cases where ports may not have enough dock frontage, for example, ports can use innovative solutions like floating assembly platforms to provide more area and support. Port assessments should also include potential impacts on the environment, local stakeholders and tribes, and seek the best location considering these impacts.

Consequences and impact. Without upgrades to regional ports, large-scale Great Lakes wind energy development will not be possible. Identifying and upgrading suitable ports will help enable large-scale development of Great Lakes wind energy and, with the proper investment in vessels and manufacturing, would allow for deployment of 15-MW wind turbines, which will lower costs and help projects compete with other energy sources. These activities are necessary to achieve the Advanced Research Technology Scenario.

Recommended research activities include:

- Specifying port requirements for various Great Lakes wind energy development scenarios and coordinating studies with technology-specific design alternatives (level of effort: $200,000−$500,000, timeline: 6 months−1 year)
- Surveying suitability of top-tier Great Lakes ports for wind energy development including site visits to determine overall feasibility, current space and weight capacities, and investment needed for upgrades for various development scenarios (level of effort: $1,000,000 to $1,500,000 million, timeline: ~1 year)
- Developing innovative port upgrade solutions, such as dry docks, floating crane barges, or submersible barges to facilitate the unique assembly and deployment of fixed-bottom and floating substructures on the Great Lakes, thereby enabling the deployment of

substructures that otherwise would not be feasible (level of effort: >$2,000,000, timeline: 3−5 years).

4.2.3 Develop Supply Chain Strategies

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	No	Yes	Yes	Low

Description. Innovative options are needed for Great Lakes wind energy supply chain development, given the physical limitations of the Great Lakes-St. Lawrence Seaway system. There is significant uncertainty about what manufacturing facilities could be adapted for domestic substructure and wind turbine component production, how those components would be transported to assembly ports, how the port would assemble the systems, and what size cranes would be required. The specific methods of manufacturing components to enable the assembly and installation of 15-MW-class fixed-bottom or floating wind turbines are generally design-specific, and the industrialization of the supply chain should be considered during the initial design phase.

The methods of transporting the system components to port for assembly are uncertain and technology dependent. Several actions could help create new transportation options and more flexibility for supply chain investors, including using larger vessels; innovations in highway, rail, or inland waterway transportation methods; strategic selection of materials; assessing the cost impact of manufacturing facility distance from ports; and early selection of manufacturing locations.

Consequences and impact. Strategies to advance the production of wind energy components on the Great Lakes will be crucial for project planning and bankability. Without this, high uncertainty could increase project risk or drive production overseas. A well-developed supply chain plan based on the requirements of Great Lakes wind energy development will decrease costs and increase local participation in the projects. Addressing this challenge is essential to ensuring that energy justice and equity issues are addressed and that supply chain investments are prioritized with local communities in mind.

Recommended research activities include:

- Surveying current manufacturing facilities in the region, such as land-based tower manufacturers or steel manufacturers, and their capacity to work with Great Lakes wind energy components (level of effort: $200,000−$500,000, timeline: 6 months−1 year)
- Determining feasible solutions of either upgrading existing manufacturing facilities, building new ones, or sourcing from other locations; investigating material alternatives to determine the most competitive regional solutions (level of effort: $1−$2 million, timeline: 3−5 years)
- Developing innovative solutions to transport large components from possible regional, national, or international manufacturing facilities to suitable Great Lakes ports, or co-

locating manufacturing facilities near a port (level of effort: $200,000–$500,000, timeline: 6 months–1 year)

- Designing new component assembly solutions based on current port capacities (level of effort: $1–$2 million, timeline: 1–3 years).

4.2.4 Assess Canadian Infrastructure Opportunities

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
3	No	No	Yes	Low

Description. Collaborating with Canada on Great Lakes wind energy could lead to additional feasible ports and potential vessels for the regional supply chain and infrastructure. For example, most of the larger, more developed ports on Lake Ontario are on the Canadian side, which could significantly increase the opportunity in Lake Ontario. The challenge includes the difficulties of international collaboration and Canadian acceptance of Great Lakes wind energy. The Jones Act, which requires that any vessel traveling between U.S. ports be built, registered, owned, and crewed by U.S. citizens, would need to be considered in any potential collaboration with Canadian ports and vessels.

Consequences and impact. Great Lakes wind energy is not dependent on Canada, but there could be opportunities and advancements that Canada could offer, such as ports and vessels, to improve the overall timeline of Great Lakes wind energy deployment. Canadian collaboration could foster a better relationship regarding Great Lakes wind energy as well as provide new opportunities that would otherwise be overlooked.

Recommended research activities include:

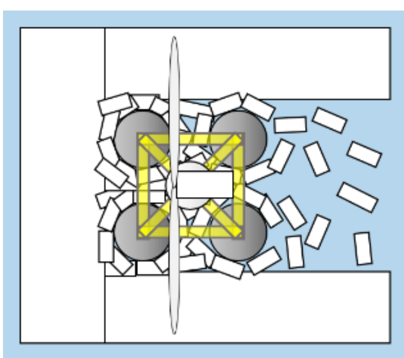
- Evaluating Canada's interest in future Great Lakes wind energy from a political and regulatory standpoint (level of effort: $200,000–$500,000, timeline: 3–5 years)
- Assessing Canadian ports, vessels, and manufacturing capabilities that could potentially fill essential supply chain gaps in Great Lakes wind energy development while considering Jones Act limitations (level of effort: $200,000–$500,000, timeline: 6 months–1 year)
- Quantifying economic impacts of using Canadian assets to augment U.S. Great Lakes wind energy infrastructure and evaluate the pros and cons for different Great Lakes wind energy build-out scenarios (level of effort: $200,000–$500,000, timeline: 6 months–1 year).

5 Technology Options

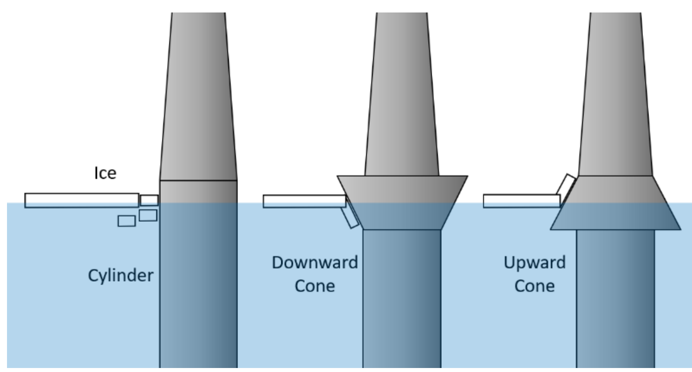
The technology necessary for Great Lakes wind energy is constrained by many factors. The physical ice environment of the region dictates unique operating and extreme conditions that the wind turbine systems must withstand, and rules out certain substructure types. However, deficiencies in the existing infrastructure and supply chain are the primary constraints on wind turbine size and the technology that can be deployed. These factors must be considered to design feasible and cost-effective Great Lakes wind energy technologies.

One of the unique aspects of the Great Lakes environment is the presence of level ice on the lake surface in the winter months. Lake ice can take many forms but is commonly seen as sheets of ice on the water surface that drift across the lakes (ice floes) during spring thaws. In some locations and extreme weather conditions, lake ice can potentially exert structural loads greater than the expected aerodynamic or hydrodynamic loads on the system. Ice ridges, which are layered aggregations of broken ice sheets (see Section 3), may produce the largest loads on a wind energy support structure. Ice ridge sizes and their frequencies of occurrence are generally unknown.

There are two primary methods to mitigate ice loads on a structure, but additional design measures may be needed for floating systems. The first method is to design the structure with a slender waterline profile to prevent ice from accumulating in front of the structure or between structural legs (Figure 14a). The second is to outfit the structure with an ice cone near the waterline to induce a bending failure mode of the ice sheet, which lessens loads on the structure considerably (Figure 14b).



(a)



(b)

Figure 14. Nonslender waterline profiles create potential for ice jamming (a), and ice cones induce the bending moment of failure of ice, which exerts smaller loads on the structure (b). ***Image by NREL***

The wind speeds and sea states of the Great Lakes are comparable to the conditions of conventional offshore wind energy development areas like the U.S. North Atlantic. However, there are environmental conditions that are unique to the Great Lakes that will require modifying the normal offshore wind system design process and technology design load envelopes. For example, lake spray ice, which can occur when wind lifts water droplets from the surface of unfrozen lakes in subfreezing temperatures, could allow ice to accumulate on the tower and substructure. This ice build-up could add mass to the structure and alter the dynamic properties of the system. Similarly, softer soils in the Great Lakes combined with shallow bedrock may require different fixed-bottom support structures or anchors. Interannual variations of water levels in the lakes have the potential to affect the buoyancy and mooring system properties of floating substructures or can affect the placement of ice cones on fixed substructures. Great Lakes systems will have a distinct advantage, however, because they will not be subject to ocean-based environmental factors, such as corrosion due to saltwater.

As described in Section 4.0, the narrow locks of the St. Lawrence Seaway prevent large, conventional WTIVs from entering the Great Lakes, and the current ports are not large enough to support large-scale offshore wind turbine assembly and installation. Smaller-sized wind turbines and fixed-bottom substructures have potential to be installed using smaller installation vessels that can navigate the locks, but alternative installation solutions such as retrofitted regional vessels or custom-built vessels will be needed to deploy larger fixed-bottom technologies. Smaller-sized wind turbines and floating substructures also have potential for assembly at port, but upgrades to ports, or completely new ports, will be needed for the larger floating technologies. The availability and designs of cable-laying vessels may also influence the power cable layout.

Great Lakes wind energy development may also be constrained by various siting considerations, such as viewshed limits or export cable routing challenges, but also less constrained by some conventional offshore wind siting considerations, such as expansive commercial fishing or unexplored ordinances. Additionally, the lake wildlife and lakebed conditions can influence the fixed-bottom foundation or anchor technology. Each of these factors should be considered when designing and selecting Great Lakes wind energy technology.

The following sections discuss the current scenarios of fixed-bottom substructures, floating substructures, and wind turbines for Great Lakes wind energy development, and the key challenges found specifically in that environment.

5.1 Fixed-Bottom Foundations

At the end of 2021 over 50 GW of offshore wind energy has been installed globally and all but 123 MW are fixed-bottom offshore wind installations (Musial et al. 2022). Fixed-bottom support structures provide a rigid connection between the wind turbine and lakebed and are currently the most economical option in water depths less than 60 m (Musial et al. 2022).

The design of offshore wind turbine technology follows International Electrotechnical Commission (IEC) 61400-3-1 standards (International Electrotechnical Commission. 2019). The design procedure requires developing a basis for design and evaluating specific design load cases (DLCs) based on the environment the wind turbine will be placed in. This procedure is well-established for offshore wind energy sites in the ocean, but Great Lakes wind conditions present many unique challenges that need to be addressed.

5.1.1 Current Situation

Currently, fixed-bottom technology in the Great Lakes would follow IEC 61400-3-1 design and guidance provided in relevant sections of the newly published ANSI/ACP OCPR-1-2022 (American National Standards Institute 2022). This guidance includes wind and wave conditions, wind and wave directionalities, current conditions, and water level conditions for design situations such as power production or parked. The IEC standards include DLCs for fixed-bottom offshore wind turbines in the presence of ice. These DLCs have been developed for conventional, ocean-based offshore wind energy development, but they do not consider the Great Lakes environment. Depending on the site characterization, the most extreme environmental conditions may not be captured in these DLCs. Fixed-bottom technologies can be adequately designed using these DLCs, but there is higher uncertainty due to a lack of understanding in characterizing the extreme loads, such as the force imparted on structures from extreme ice ridges associated with ice floes.

The characterization of ice ridges and the development of more accurate extreme ice DLCs would enable better ice design modeling tools to assess structural loading to design reliable fixed-bottom substructures for the Great Lakes. These tools include the effects of not only ice but wind, waves, and currents on the substructure. Ice-structure interaction models have been previously developed for various cold-climate engineering applications but are not able to model the extreme loads caused by ice ridges. OpenFAST, which is a program developed by NREL to simulate the coupled dynamics of offshore wind turbine systems, contains two ice modules, IceDyn and IceFloe, both of which include various ice models to simulate the ice loads on an offshore structure. IceDyn and IceFloe can be used to model interactions between Great Lakes ice and fixed-bottom structures; however, these models are largely unvalidated for Great Lakes conditions.

Other modeling approaches have previously been used to model ice-structure interactions on offshore structures in freshwater lakes. The Icebreaker project, led by LEEDCo, developed their own process to determine ice ridge loads on fixed-bottom substructures, which utilized the International Organization for Standardization 19906 standards (International Organization for Standardization 2010) and their own estimation methods (Allyn and Croasdale 2016). This work was based on a parametric comparison with the Confederation Bridge, which connects Prince Edward Island and New Brunswick, Canada, is over 8 miles long, and supported by 44 conical piers designed to break ice. Ice-structure modeling of ice ridges in the Great Lakes could likely build on existing standards and experience with bridges and piers, and LEEDCo's ice ridge load estimation method.

Previous offshore wind energy projects in the Baltic region have been developed in brackish or fresh waters, such as Lake Vanern in Sweden. The Tahkoluoto offshore wind farm project, on the west coast of Finland in the Gulf of Bothnia, created an ice design basis from a lighthouse test cone ice data collection project and experience from 200 local lighthouses and channel markers, which was used to calculate the characteristic ice-loading condition on gravity-based offshore wind turbines due to an ice ridge impact (Eranti et al. 2011). Previous load estimation experience, like the Tahkoluoto offshore wind farm and other ice-structure interaction load estimation methods and models in industry (e.g., Gravesen and Kärnä 2009), can inform the extreme ice ridge characterization and loads estimation development for fixed-bottom substructures in the Great Lakes, but a comprehensive investigation into their assumptions and validity will be needed. Collaboration with research entities experienced with ice-structure modeling would provide further insights into the capabilities of tools used in industry. The present level of uncertainty in modeling these extreme ice conditions could lead to under- or overdesigned structures in an extreme Great Lakes environment.

Designs of fixed-bottom substructures for Great Lakes wind energy development today would likely employ technologies that are conventionally used in ocean-based offshore wind plants, because they would be the most technologically ready systems. A study was conducted to determine the feasibility of fixed-bottom substructures for the Great Lakes based on their ease of installation, lakebed compatibility, ice-structure loading, local manufacturability, system cost, and technology readiness (NYSERDA 2022a). The general results of the feasibility study are shown in Figure 15.

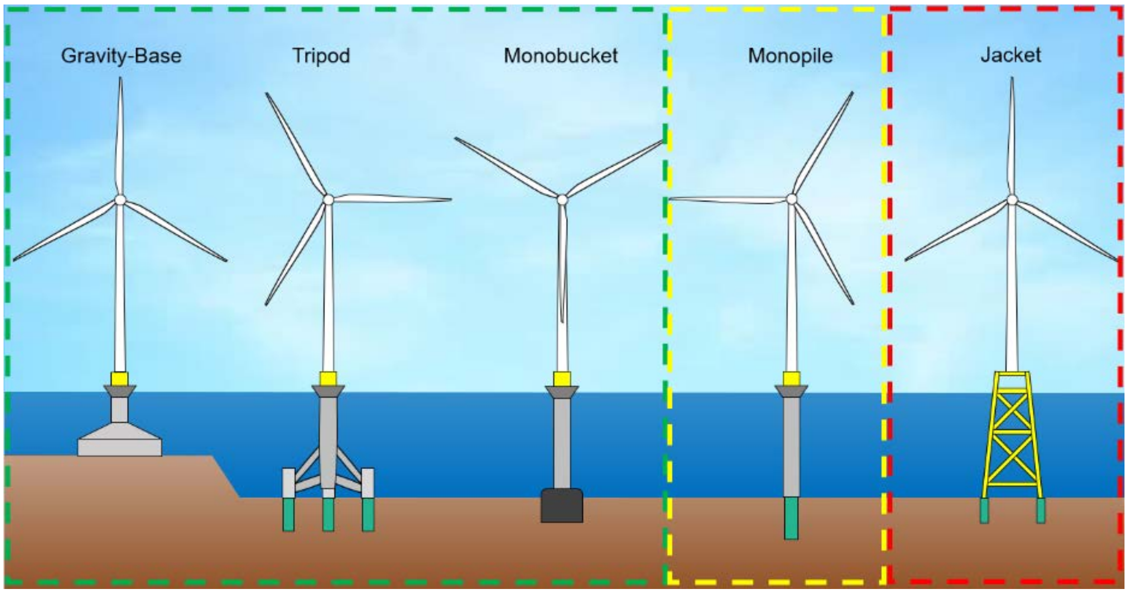


Figure 15. Possible fixed-bottom substructures for Great Lakes wind energy (green: most favorable, yellow: less favorable, red: not favorable). ***Image by NREL***

As indicated in Figure 15, gravity-based foundations, tripods, and monobuckets are more suitable fixed-bottom substructures for Great Lakes wind energy, whereas monopiles and jackets are less favorable. Monopiles require large, pile-driving installation vessels that are currently not available in the Great Lakes and are typically too wide to access the lakes through the locks of the St. Lawrence Seaway. Also, the relatively softer soils and low depths to bedrock of Lake Erie would not be conducive to conventional monopile designs. Jackets have the high potential of ice accumulation and jamming between the legs, which would create significantly higher loads on the structure. The remaining substructures may be technically feasible in the Great Lakes, but would need further development for the technology to be economically feasible. Gravity-based foundations would require proper lakebed preparation that would need to accommodate softer soils. Tripods are technically feasible but are perceived to be expensive, and monobuckets are less mature and as a result may have a higher risk. The best-suited fixed-bottom substructure is likely an adaptation of one of these more conventional substructures, or it could be a completely new design concept that meets the specific environmental and logistical requirements of the Great Lakes.

5.1.2 Key Challenges

The following lists a set of the most important challenges for fixed-bottom Great Lakes wind energy development that would need to be addressed with further research.

5.1.2.1 Develop Design Basis for Fixed-Bottom Foundations

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	No	Yes	Medium

Description. Because of uncertainty about the magnitude of ice ridges and potential ice buildup caused by lake spray in the Great Lakes, the full scope of environmental conditions has not yet been characterized. Combined with other environmental conditions, additional design loads may be produced that expand the design load envelope. The current DLCs prescribed by IEC 61400-3-1 may not fully account for all the environmental conditions in the Great Lakes. Therefore, the current DLCs need to be reevaluated for this environment. Specifically, the extreme ice condition is not well-defined, such as pressure from haphazardly arranged (hummocked) ice and ice ridges. The most extreme load condition may also include combinations with loads from waves or effects from lake spray ice buildup. The degree to which the current DLCs provide an adequate load characterization for a fixed-bottom substructure design needs to be further verified for the Great Lakes environment. Early-stage deployments and pilot projects could help validate the fixed-bottom design basis.

Consequences and impact. Without an accurate assessment of the loads for Great Lakes wind energy, fixed-bottom substructure systems cannot be accurately designed, leading to uncertainty that can increase project risk and cost. This potential decrease in system reliability could negatively impact deployment potential, increase costs, and produce designs unable to withstand the Great Lakes environment. Without a common understanding of the physical basis for determining these new loads, regulators will need to rely on developer's consultants to determine best practices. A more comprehensive assessment of the design basis would result in more reliable substructure designs for the Great Lakes, which would significantly lower the cost of development and increase project bankability.

Recommended research activities include:

- Developing a comprehensive, physics-based design basis for fixed-bottom wind turbines considering all conditions, especially those related to ice (level of effort: \$1−\$2 million, timeline: 2−3 years)
- Verifying the Great Lakes climate through data collection and determining what combinations of each produce the highest loads on the wind turbine (level of effort: \$1−\$2 million, timeline: 3−5 years).

5.1.2.2 Advance Ice-Structure Interaction Modeling (Fixed-Bottom Foundations)

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. The presence of freshwater ice in the Great Lakes creates additional environmental load considerations for wind turbine designs. As a result, ice-structure load prediction models are needed to accurately quantify the extreme ice loads on an offshore structure. The presumed design-driving extreme load events on a fixed-bottom substructure are thought to be caused by ice ridges, which are poorly understood because they are rare and hard to characterize comprehensively. Therefore, they are also not considered in the ice-structure models. The challenge lies in the uncertainty of design modeling tools and obtaining the proper input data to simulate the extreme design-driving load events on fixed-bottom substructures. Open-source ice-structure interaction modeling tools, such as IceDyn and IceFloe, are not programmed to model the extreme load events of ice ridges and have not been thoroughly validated by experimental data even for more common ice floe events. Other ice-structure interaction models exist in industry and have been used for offshore wind projects in freezing, freshwater locations like the Baltic region, but a full assessment of their capabilities and validity is required.

Consequences and impact. Improper or immature modeling of ice loading on fixed-bottom substructures in the Great Lakes can lead to high design uncertainty and unreliable, costly systems. Lacking the capability to accurately model the extreme ice DLCs would lead to highly uncertain designs and higher costs, resulting in lower confidence by investors that could negatively impact deployment and cost. Proper ice-structure modeling tools for fixed-bottom substructures would lower cost and increase the reliability of Great Lakes wind energy designs.

Recommended research activities include:

- Investigating the cost and capabilities of existing fixed-bottom ice-structure interaction models in industry that may be available to represent the critical ice ridge DLCs, including cooperating with international research entities experienced in ice-structure modeling (level of effort: $500,000−$1 million, timeline: <6 months)
- Adapting existing ice-structure interaction models and methods to account for ice ridge effects, if other industry models are not feasible (level of effort: $1−$2 million, timeline: 1−3 years)
- Conducting a comprehensive field data campaign of Great Lakes observations to create a validation database for ice load modeling. This campaign would be conducted in cooperation with national and international partners experienced in ice climate observations (level of effort: >$2 million, timeline: up to 5 years)
- Physical modeling to characterize ice structures over the Great Lakes should be investigated and developed. Data campaigns should be conducted in parallel with high-fidelity numerical model development to simulate the ice conditions over periods that represent the design life. Models should be conducted on a high-fidelity geospatial plane and include characterizations of extreme ice ridges (level of effort: $3–$5 million, timeline: up to 5 years).

5.1.2.3 Develop Alternative Fixed-Bottom Substructure Designs and Solutions

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. The environmental and physical constraints of the Great Lakes limit the types and sizes of technology that can be used for fixed-bottom wind energy development. Ocean-based fixed-bottom technology being used on the Atlantic, such as WTIVs and substructures like monopiles and jackets, were not designed to access the Great Lakes or to survive ice climates. The narrow locks of the St. Lawrence River prevent conventional installation vessels from accessing the Great Lakes. In addition, winter ice floes could create excessively high ice loads on nonslender substructures like jackets, and the lakebed soils may be too soft to support laterally loaded piles like monopiles. The existing ports are also not suitable to handle the size of expected wind turbines and substructure components for 15-MW-class turbine deployment. These limitations to the fixed-bottom substructure designs and installation methods require unique solutions or adaptations of the conventional designs to enable use of 15-MW-class offshore wind energy supply chains and their associated cost reductions. Technology adaptations or novel designs would be needed to assemble, install, operate, and maintain fixed-bottom wind turbine systems.

Consequences and impact. Without considering alternative fixed-bottom substructure designs for this region, fixed-bottom Great Lakes wind energy development would be limited to smaller 6-MW wind turbines and substructures that are suboptimal. The smaller, land-based turbine sizes would add costs to projects. The successful development and implementation of custom, or adapted, Great Lakes fixed-bottom substructure technology that avoids the environmental and physical limitations of the Great Lakes would enable the use of 15-MW-class wind turbines and lower the overall cost.

Recommended research activities include:

- Assessing the technical feasibility, cost, and local benefits of existing fixed-bottom substructure designs, installation strategies, ports, and heavy-lift equipment (cranes) to determine if adaptations to those designs and installation methods are possible for Great Lakes wind energy (level of effort: $200,000−$500,000, timeline: 6 months−1 year)
- Upgrading design tools to accurately model new, ice-tolerant Great Lakes systems that include assembly and installation considerations; reviewing and recommending upgrades to design standards depending on novel substructure features (level of effort: $1−$2 million, timeline: 3−5 years)
- Developing custom, fixed-bottom substructure concepts and installation strategies optimized for the Great Lakes environment that would address the major limiting factors of the region, such as vessels, ice loading, manufacturability, and the suitability for softer soils. The designs should address unique port design and vessel requirements, and novel self-installing methods and solutions (level of effort: >$2 million, timeline: >5 years).

5.2 Floating Substructures

There has been a total of 123 MW of floating offshore wind energy installed in the world as of the end of 2021 (Musial et al. 2022). Floating substructures are used to support offshore wind turbines in water depths greater than 60 m, where fixed-bottom substructures are no longer economically feasible (Musial et al. 2022). Based on IEC 61400-3-2 standards (IEC 2019b), a floating offshore wind turbine is defined as being subject to hydrodynamic loading and supported by a buoyancy and station-keeping system. It is assumed that all Great Lakes, except for Lake Erie, would use floating substructures, because most of the water depths in Lake Ontario, Lake Huron, Lake Michigan, and Lake Superior exceed 60 m. There are significant shallow areas in these deeper lakers that could support fixed-bottom Great Lakes wind energy but most of these resource areas are close to shore and could potentially have greater design and siting challenges than floating wind.

There have been many types of floating substructures (and associated mooring systems) developed for offshore wind applications. However, the Great Lakes present many challenges that need to be addressed.

5.2.1 Current Situation

The floating IEC standards currently do not include any DLCs for floating offshore wind turbines in the presence of ice and there are no floating demonstration projects in ice environments (IEC 2019b). The DLCs used for floating turbine design were developed for conventional, ocean-based offshore wind systems, but not for the Great Lakes ice environment. For floating Great Lakes wind energy technology, DLCs will need to be developed that consider ice loads on the substructure, the mooring system, and the dynamic cables in the water column.

Proper floating wind design methods for this region must include the ability to simulate the extreme ice loads on a floating structure. The effects of ice on floating substructures, as well as mooring system components and power cables, is not well-understood. IceDyn and IceFloe, the two ice-structure models that are part of NREL's OpenFAST suite, can only simulate ice effects on fixed-bottom substructures. Designing floating technology for the Great Lakes would involve further investment in design tools for ice loads on floating structures with six degrees of freedom.

Designs of floating substructures for Great Lakes wind energy development today would likely employ technologies that are used in ocean-based offshore wind plants, as well as oil-and-gas systems, because they would be the most technologically ready. The *New York Great Lakes Feasibility Study* led by NREL assessed floating substructures in the region based on their ease of installation, ice-structure loading, local manufacturability, system cost, and technology readiness (NYSERDA 2022a). The general results of the feasibility study are shown in Figure 16.

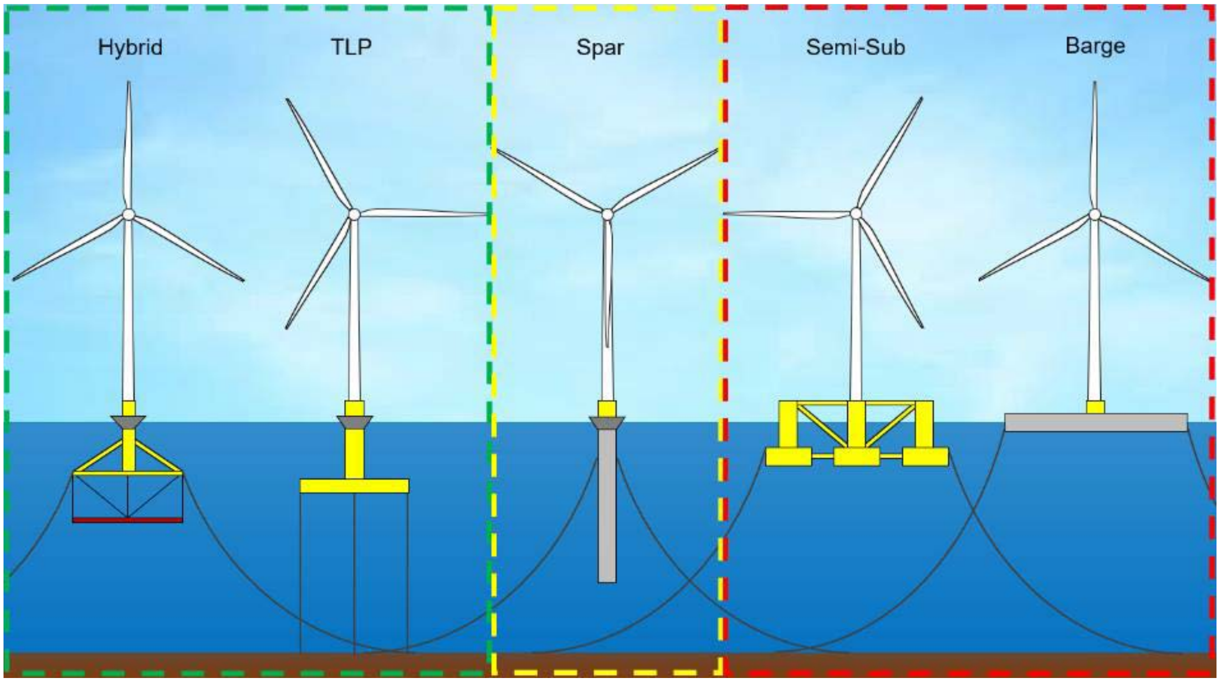


Figure 16. Common floating substructures that could be used for Great Lakes wind energy (green: most favorable, yellow: less favorable, red: not favorable). ***Image by NREL***

From the feasibility assessment, and as indicated in Figure 16, floating substructures like hybrids and tension-leg platforms (TLPs) would be more favorable for the Great Lakes, whereas spars, semisubmersibles, and barges would be less favorable. Even though barges can be made from cement, which can be easily fabricated and withstand ice loads more efficiently than hollow, tubular steel structures, they have large, nonslender waterplane areas, which would create excessively high ice loads on the substructure. Semisubmersibles have multiple buoyancy tanks crossing the waterplane, which would also create the potential for large and excessively high ice loads on the structure due to ice jamming. Spars are more favorable than barges and semisubmersibles because of their slender waterplane areas but may still not be feasible due to their deep draft. The Great Lakes do not have deep channel ports to support upright spar assembly and installation. TLPs are the only remaining conventional floating substructure that would be feasible for the Great Lakes because they can be configured (with additional vessels) for stability during assembly at quayside and load out while maintaining a slender waterline profile. The highest concern for floating offshore wind TLPs is their technology readiness, relative to other conventional floating substructures.

Other innovations in floating substructure design use adaptations between spars and semisubmersibles. One example is the TetraSpar, which is a tetrahedral-shaped substructure made up of tubular components that supports the attachment of the keel (Figure 17). The substructure components were designed to be modular to facilitate ease of transportation and component assembly. The keel can be ballasted to help float the structure like a semisubmersible or spar, and can help tow the structure to site without an installation vessel (Borg et al. 2020). The TetraSpar would have to be adapted to simplify the substructure profile at the waterline, but these modifications would be relatively straightforward and would not introduce additional cost or risk.

Figure 17. The TetraSpar substructure concept. ***Image from Borg et al. (2020)***

The TetraSpar and TLP would be relatively well-suited for the Great Lakes environment, given proper port depths and requirements to support the substructure assembly. Tilt-down spars could also be feasible but would require a large investment into the assembly and installation infrastructure on the Great Lakes. The most suitable floating substructure is likely an adaptation of the conventional floating substructures, or a new design concept that meets the specific environmental and logistical requirements of the Great Lakes.

For the station-keeping system, mooring lines can be made of different materials like chain, wire rope, or synthetic rope, and organized in different configurations around the floating substructure, in either taut, semi-taut, or catenary configurations. There are also many anchors that can be used for floating applications, such as deadweight (gravity), drag-embedment, pile, or plate anchors that can be more suitable for certain soils or mooring configurations over others. The selection of mooring line materials, mooring system configurations, and anchor types would depend on local factors like the extreme ice conditions and loads, seabed conditions, and wind power plant layout. For example, synthetic mooring lines that are gaining popularity in the offshore wind industry need to be evaluated in their ability to withstand frequent ice interactions in the Great Lakes relative to other line types.

5.2.2 Key Challenges

The following lists a set of the most important, high-level challenges to floating Great Lakes wind energy development that would need to be addressed with further research.

5.2.2.1 Develop Design Basis for Floating Substructures

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	No	Yes	Low

Description. Because of ice ridges and potential ice buildup caused by lake spray in the Great Lakes, the full scope of environmental conditions needs to be characterized. Combinations of environmental conditions produce different loads on an offshore structure and subsequently, different DLCs may need to be considered. The challenge lies in the uncertainty of defining the full set of design conditions and how they apply to floating systems. Ice ridges may produce the most extreme ice loading condition, but other environmental conditions may add to those loads. The current standards do not specify any DLCs that account for ice or any combination of ice and other environmental effects on floating support structures. Early-stage deployments and pilot projects should be established to validate the research in this challenge area.

Consequences and impact. Without accurate floating DLCs for Great Lakes wind energy, the most extreme loads on a system cannot be accurately modeled. This uncertainty can result in decreased system reliability and would negatively impact deployment potential due to increased costs. Fully detailed physics-based DLCs developed for these icy environments would result in more reliable substructure designs, which would significantly lower the cost of development and project bankability.

Recommended research activities include:

- Developing a comprehensive, physics-based design basis for floating wind turbines considering all conditions, especially those related to an ice environment (level of effort: \$1−\$2 million, timeline: 1−3 years)
- Conducting a comprehensive field data campaign of Great Lakes observations to create a validation database for ice load modeling in conjunction with fixed-bottom challenge area. This campaign would be conducted in cooperation with national and international partners experienced in ice climate observations (level of effort: >\$2 million, timeline: up to 5 years).
- Physical modeling to characterize ice structures over the Great Lakes should be investigated and developed. Data campaigns should be conducted in parallel with high-fidelity numerical model development to simulate the ice conditions over periods that represent the design life. Models should be conducted on a high-fidelity geospatial plane and include characterizations of extreme ice ridges and performed in conjunction with fixed-bottom challenges (level of effort: \$3−\$5 million, timeline: up to 5 years).

5.2.2.2 Advance Ice-Structure Interaction Modeling (Floating Substructures)

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Low

Description. The presence of freshwater ice in the Great Lakes creates additional environmental loads to consider for wind turbine designs. As a result, ice-structure load prediction models are needed to accurately quantify the extreme ice loads on a Great Lakes wind energy structure. These models currently predict loads for various ice-structure interactions on offshore substructures, but typically assume the substructure is fixed. Floating offshore wind substructures can offset from their original position by tens of meters, which can affect the relative motions between the substructure and the floating ice and significantly alter their interaction. Also, the mooring system models would need to account for the change in platform properties, as well as any effects the ice may have directly on the mooring system. The challenge lies in the uncertainty of the input data for extreme ice events and the lack of ice-structure interaction tools that model the design-driving load events on floating substructures.

Consequences and impact. The inaccuracy in modeling ice loading on floating substructures in the Great Lakes would lead to high design uncertainty and costly systems. The extreme-ice DLCs of the Great Lakes for floating substructures are not currently captured in simulations, such that the necessary sizes of designs capable of withstanding the extreme loads would be highly uncertain. This uncertainty would result in lower confidence by investors and negatively impact deployment. With accessible and reliable ice-structure modeling tools, floating substructures can be accurately modeled for the expected extreme ice conditions of the Great Lakes and produce lower-cost designs.

Recommended research activities include:

- Conducting a comprehensive investigation of the cost and capabilities of existing floating ice-structure interaction models in the industry while coordinating with international research entities with experience in ice-structure interaction modeling, and identifying gaps for future code development (level of effort: $500,000–$1 million, timeline: <6 months)
- Developing and validating new, ice-structure interaction models for floating offshore systems that can account for ice floes and ice ridge effects (level of effort: $1–$2 million, timeline: 3–5 years).

5.2.2.3 Alternative Floating Substructure Designs

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. The environmental and physical constraints of the Great Lakes limit the types and sizes of technology that can be used for floating wind energy development. Early-stage ocean-based floating technology being deployed around the world has not been designed to survive the ice climates of the Great Lakes. The primary limitation for floating wind on the Great Lakes is its ability to resist these additional ice loads, both on the substructures, mooring systems, and dynamic cables. Additionally, large-scale 15-MW-class wind turbine assembly and installation of floating substructures would typically occur at quayside, but the Great Lakes ports do not currently have those capabilities. The port requirements for floating wind systems in the Great Lakes would essentially be the same as for floating offshore wind in the ocean, meaning that future port development could use current port development processes and the supply chains for larger wind turbines.

These limitations require unique solutions or adaptations of conventional designs to use the 15-MW-class offshore wind supply chains and their associated cost reductions. Technology adaptations or novel designs would be needed to enable assembly, installation, operation, and maintenance for floating wind turbine systems.

Consequences and impact. Without considering alternative floating substructure designs for the Great Lakes, wind energy development would be limited to substructures such as TLPs, hybrids, or tilt-down spars. These substructure designs are in more nascent stages of development for floating offshore wind but would be comparable to a bespoke floating system designed and adapted for the Great Lakes. The successful development and implementation of custom, or adapted, Great Lakes floating substructure technology that avoids the environmental and physical limitations of the region would enable the use of 15-MW wind turbines and lower the overall cost for Great Lakes wind energy.

Recommended research activities include:

- Assessing the viability and cost of existing floating substructure designs, installation strategies, ports, and heavy-lift equipment (cranes) to determine if adaptations to those designs and installation methods are possible for Great Lakes wind energy (level of effort: $200,000−$500,000, timeline: 6 months−1 year)
- Upgrading design tools to accurately model new, ice-tolerant Great Lakes systems that include assembly and installation considerations; reviewing and upgrading design standards (level of effort: $1−$2 million, timeline: 3−5 years)
- Exploring innovation space for the development of custom, floating substructure concepts and installation strategies optimized for the Great Lakes environment that would address the major limiting factors in the region, such as vessels, ports, and ice loading. Multiple designs should address efficient port design and vessel requirements (level of effort: >$2 million, timeline: >5 years).

5.3 Wind Turbines

This section describes the challenges encountered for the wind turbine itself for Great Lakes wind energy. The two primary issues are the scale of the turbine that can be used on the lakes, given the uncertainty of installation methods and required vessels, and the unique ice climate issues that may arise in a freshwater, cold climate.

5.3.1 Current Situation

The methods for installing wind turbines onto substructures follow the challenges outlined in Section 4.0 for fixed-bottom and floating wind systems. The primary port limitations that were identified can be summarized as:

- All ports will need significant upgrades.
- Shallow drafts may limit vessel access and some types of technology adaptations.
- No ports have sufficient crane capacity for installation and assembly of wind turbines at quayside.

The primary vessel limitations that were identified can be summarized as:

- Full-sized WTIV vessels for on-site turbine installations are unlikely to be available.
- Some vessels may not be able to operate in ice environments.

Due to the uncertainty of adequate installation vessels or solutions on the lakes, and the capabilities and constraints of ports to support large wind turbine components, Great Lakes wind energy may need to use smaller-sized wind turbines (6-MW class) in early-stage projects until the infrastructure and substructure technology constraints can be addressed. The advantages of smaller turbines are that they are lighter, less expensive in some cases (as they are already in serial production), offer more synergies with established U.S. supply chains for land-based and offshore wind, and their components are easier to transport.

Land-based wind turbines are growing in size and are now available up to 7.2 MW. These turbines are considered the default option for the Current Scenario because near-term options for deployment are limited to using the existing infrastructure with more modest upgrades. These turbines will still require custom installation vessels and port improvements but the cost of these vessels and improvements will likely be significantly lower than for larger offshore turbines. Another advantage is that smaller turbines are more optimized for Great Lakes wind conditions and offer lower-specific-power ratings than what is available in the less-mature 15-MW-class offshore turbines, which enable increased capacity factors for Great Lakes conditions. Because of the infrastructure and technology constraints at the time of planning, LEEDCo selected the smaller, land-based Vestas V126-3.45 turbine for its 21-MW pilot project 7 miles north of Cleveland in Lake Erie. Table 4 shows a range of available offshore and land-based wind turbines.

The disadvantage of land-based wind turbines is that a greater number of turbines is required for a given plant capacity. As a result, installation and maintenance costs are higher, and more array cables are needed. However, until port infrastructure or alternative installation solutions are developed to accommodate the larger 15-MW-class offshore turbines, smaller land-based turbines may be the most feasible option for the Great Lakes.

One example of a similar lake application is the Windpark Fryslân in the Netherlands. It is the largest inland freshwater wind plant in the world and is deployed in relatively shallow waters. The developer selected Siemens 4.3-MW turbines with 130-m rotor diameters.

Table 4. Characteristics of Commercially Available 4- to 7-MW Wind Turbines

Wind Turbine	Rating (MW)	Rotor Diameter (m)	Application	Specific Power (watts/m^2)
Vestas V226	15	236	Offshore	343
Siemens SG 14	14	222		362
GE Haliade X	14	220		368
Nordex N133/4.8	4.8	133	Land-Based	346
SGRE 4.X	5	132		365
Vestas V162-6.8	7.2	162		349
Vestas V162-6.2	6.2	162		301
Vestas V150-6.0	6	150		340
SGRE 5.X	6.6	155		350
SGRE 4.X	5	145		303
Vestas V126-3.45	3.45	126		277
SGRE 6.6 170	6.6	170		291
Vestas V163-4.5	4.5	163		216
Vestas V172-7.2	7.2	172		310
GE Cypress	5.3	158		270
Nordex N163/6.X	6.5	163		311
Nordex N163/5.X	5.5	163		264
Nordex N149/5.X	5.5	149		315

In the current situation, there are some alternative methods that can be used to install wind turbines in the near term. The barge-mounted crane is one alternative for shallow-water wind turbine installations with limited access to WTIVs. This method was used in the Netherlands to install monopiles and wind turbines. Sarens constructed a jack-up barge made of 88 modular barges and a PC6800 1,250-ton crawler crane in a pedestal mount configuration for the Windpark Fryslân (Sarens 2021; Selby 2019). The barge and crane were used to install 89 4.3-MW turbines on 115-m towers and 39-m monopiles (Figure 18).

Figure 18. Sarens Soccer Pitch modular crane barge. ***Photo from Sarens (2021)***

Another alternative wind turbine installation solution is to use self-installing technologies. One type of self-installing technology, developed by WindSpider, uses the wind turbine tower as the body of the crane and can lift more than 1,200 metric tons to the height of the nacelle, eliminating the need for a vessel with the same required crane capacity (Knauber 2022). Self-installing technologies can decrease the installation requirements of wind turbines, as well as potentially create room for design improvements of the wind turbine itself that were previously limited by the installation process. These self-installing methods are novel and largely unproven, but they may have a more compelling value proposition in the Great Lakes where many other installation options are not feasible.

Wind turbines in the Great Lakes would be subject to many cold-weather effects including icing on the surface of the blades, towers, and substructures due to atmospheric conditions or from direct lake spray. Standard cold weather options are offered by manufacturers for ice detection, anti-ice materials and coatings, and systems that heat the leading edge of the blades (Nordex 2022a; Vestas 2022) to prevent and remove ice buildup on blades (Siemens Gamesa 2018). Several land-based turbine manufacturers offer extended operating temperature options and a minimum operational temperature of -30°C and survival temperatures to -40°C (Vestas 2022; Nordex 2022b). Other solutions are to use ice-phobic coatings on the blades or retrofit hot-air blade heating systems (Borealis Wind 2022).

Controls for Great Lakes wind turbines may need to be adapted to operate in icing conditions. Experience in the Baltic Sea has not revealed significant issues of the ice buildup from direct spray altering the loading conditions on the turbine, but little freshwater experience has been documented. However, lake spray would also be a concern for degradation of the turbine's power performance because much less ice is needed to disturb the aerodynamic performance. Turbine control mitigation strategies will likely be necessary to detect and protect the turbine from lake ice spray.

O&M is a critical challenge for Great Lakes wind energy as vessels capable of major up-tower component replacement and lifting gearboxes, blades, and generator components to nacelle heights will likely be required for servicing fixed-bottom wind turbines in the unique environment of the Great Lakes. Alternative crane concepts under development for both land-based and offshore applications may reduce the need for a large O&M vessel (LiftWerx undated). A crane barge, like the Sarens barge, may be a viable option for fixed-bottom turbines in the warmer months. In the winter months, when some areas of the lakes freeze over completely for months at a time, or the weather conditions are too rough, the wind turbines may be unable to be accessed for a month or more at a time. This is not uncommon in the offshore wind industry but there may be issues specific to the Great Lakes that need to be addressed.

U.S. and Canadian icebreaking vessels in the Great Lakes keep shipping lanes open during the winter months and can likely be used for vessel O&M. If icebreakers are unavailable, helicopters may also be necessary to transport service personnel when the lakes are frozen. Otherwise, alternative O&M strategies may be needed for turbine access and repair in winter months, such as innovative technologies that can perform O&M procedures on top of frozen ice sheets.

5.3.2 Key Challenges

The following provides a set of high-level key challenges to the wind turbine designs and O&M procedures for Great Lakes wind energy development that would need to be addressed with further research.

5.3.2.1 System Engineering Modeling Tools for the Great Lakes Ice Climate

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	No	Yes	Low

Description. Ice loading effects due to freezing lake spray need to be considered in the engineering analysis. Engineering design methods need to ensure they accurately predict the loads resulting from the added mass and larger profiles. The current models do not account for these new effects and their extent is not known. As a result, designers need to take this into account but the basis for design has not yet been established. The best approach will ultimately be to mitigate these effects once they are understood.

Consequences and impact. The poor understanding of Great Lakes environmental effects could lead to lower reliability of the wind turbine system. Ice buildup on the blades can lead to rotor imbalances that can increase fatigue and degrade performance. A comprehensive understanding of these environmental conditions and turbine design upgrades to mitigate their impacts will lower the cost of deployment and risk of failure.

Recommended research activities include:

- Assessing the current design tools and upgrade methods with new site characterization data for possible ice buildup to determine gaps in the modeling processes (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Implementing the effects of new environmental conditions like freshwater lake spray into the system design and design modeling tools, and publishing information to inform designers (level of effort: $1 million, timeline: 2 years).

5.3.2.2 Develop Cold-Climate Wind Turbine Design Alternatives

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	No	Yes	Yes	Medium

Description. The design of wind turbines for cold climates commonly used on land may be implemented for Great Lakes wind energy but additional requirements may be needed to protect against unique conditions on the lake. Considerations such as lake spray freezing on the wind turbine tower and blades, winter personnel access and safety, and blade icing should contribute to the overall design of a wind turbine. Cold-climate de-icing and mitigation systems may also be needed. The challenge is to understand the extent to which ice may accumulate on the wind turbine and tower under various winter conditions and to determine the mitigation strategies and active systems that can reduce the impact.

In addition, at some locations in the Great Lakes, ice floes can drift across the lakes during the spring thaws and potentially create high loads, ice ridges, and continued battering from ice sheet fractures on the cones. To reduce the impact, and considering wave loading will already be minimal under these conditions, wind turbine sensors may be developed to detect these ice floe conditions and shut the turbine down to reduce aerodynamic thrust loads. These strategies have not been investigated but could help reduce the impact of ice loading.

Consequences and impact. Cold climate issues resulting from ice buildup on the blades and tower can have damaging consequences, but these impacts have yet to be studied. There is a high probability of serious performance and operational shortfalls that could increase the risk of failure and costs, as well as negatively impact deployment potential. Wind turbine designs that account for these effects would produce more energy and have lower costs. Therefore, addressing this issue would increase confidence for investors and lead to higher deployment potential.

Recommended research activities include:

- Quantifying potential impacts due to lake spray icing, and investigating existing design mitigation strategies that adapt wind turbine blades and towers to withstand or prevent these effects (e.g., nonstick coatings) (level of effort: $1–$2 million, timeline: 1–3 years)
- Developing wind turbine control survival methods that can detect and respond to ice floes and protect the turbine to minimize loading (level of effort: $500,000–$1 million, timeline: 1–3 years).

5.3.2.3 Adapt Operations and Maintenance Procedures for Great Lakes Conditions

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	Yes	Yes	Low

Description. Wind turbine O&M procedures need to be adapted for the vessels that are available on the lakes, and the isolated ice environments on the Great Lakes during the winter months. For conventional offshore wind farms, it is not uncommon to be unable to perform O&M on wind turbines for months at a time, for a variety of environmental and logistical reasons. For Great Lakes wind farms, depending on the lake and the amount of ice cover, O&M ports might not be accessible in the winter and O&M vessels may not be able to access the port of the turbine, even if the centers of the lakes are unfrozen. O&M vessels capable of major up-tower component replacement will likely be needed; however, there are no dedicated wind turbine O&M vessels in the Great Lakes. As a result, either new O&M vessel solutions will be needed, or the O&M strategies must include additional procedures for wind turbine access.

A suitable O&M vessel or alternative crane solution for major corrective maintenance will be required for servicing wind turbines in the Great Lakes. Crew vessels, small service vessels, and helicopters may be options for performing routine maintenance. Lake ice and winter conditions may prevent access to turbines that require maintenance, and this risk of decreased availability may be a critical factor in the project economics. Icebreakers can provide navigable transit lanes to the wind turbines, but only if the vessel and maintenance technology are suitable for the winter conditions. With O&M costs significantly contributing to a wind plant's lifecycle LCOE, these adaptations need to be determined and developed. Financial risk of O&M costs exceeding projections is large for the Great Lakes due to the lack of industry knowledge of offshore turbines in ice-prone areas and site access if lake ice is present.

Consequences and impact. Wind turbines in the Great Lakes that require maintenance may endure longer downtimes and experience overly expensive maintenance—thereby adding significantly higher cost to the project. Developing optimized and custom O&M procedures for the Great Lakes would reduce project costs, increase productivity, and improve worker safety. The best solutions, however, may not be available until turbines are deployed and developers, original equipment manufacturers, and service companies can work out the specific real-world problems.

Recommended research activities include:

- Assessing existing maintenance operations in the context of Great Lakes wind energy and determining additional operations and augmentations that are needed for this region (level of effort: $200,000−$500,000, timeline: 6 months−1 year)
- Assessing existing self-installing or self-maintaining methods that can overcome the barriers of conventional O&M procedures in the Great Lakes, and researching options for innovations in wind turbine design that can help facilitate these self-installing solutions (level of effort: $200,000−$500,000, timeline: 6 months–1 year)
- Providing industry with a range of O&M and survival strategy options to overcome the expected maintenance issues from recommended research mentioned earlier, including

improved wind turbine access during winter months (e.g., helicopter personnel transport) (level of effort: $1−$2 million, timeline: 1−3 years)

- Providing industry with O&M cost estimations using technoeconomic models with Great Lakes conditions to support the operations and survival strategies and quantify risk of wind turbine accessibility and cost of O&M. Research the cost effectiveness of various turbine access strategies, crew vessels, ice breakers, and large service vessels across conditions in the Great Lakes (level of effort: $500,000−$1 million, timeline: 1−3 years).

6 Electric Grid Interconnection and Integration

The nation has embarked on a long-term strategy to achieve zero-carbon emissions from the electricity sector by 2035 and nationwide by 2050 (The White House 2021). Wind energy is poised to contribute substantially to these goals—both on land and offshore. Of the eight states bordering the Great Lakes, only New York has no operating coal plants. If carbon-emission targets are to be met by these states, they will eventually need to retire their operating coal and natural gas plants and replace their electric-generation capabilities with clean, zero-carbon energy sources. The primary options of solar power, land-based wind, and offshore wind will be needed, but all face limitations stemming from quantity and nature of the resource (sun or wind), land availability, siting restrictions, and the ability of the existing electrical infrastructure to accept these new sources of power. Equally important is the degree to which the existing system can be upgraded and augmented to allow for larger contributions of energy from these new, clean sources. Offshore wind complements solar power both seasonally and diurnally.

6.1 Current Situation

The existing electricity grid network in the Great Lakes is congested, as discussed in Section 6.2.1.1. Consequently, although the wind resource potential in this region is substantial, the ability to connect Great Lakes wind power plants to the electric grid is severely limited at present. Points of interconnection (POI) that are most promising are at locations with an existing power plant connected to the local transmission network. Based on publicly available data and interviews with the surrounding independent system operators, these existing connections are unlikely to accommodate large amounts of power from a Great Lakes wind power plants unless the existing generation is retired or the local and associated regional transmission facilities are upgraded.

Figure 19 shows some prospective POIs for the Great Lakes region. These POIs tend to coincide with existing power plants, because the costs associated with establishing new connection infrastructure at a location not currently served by the local transmission grid would substantially exceed costs to access locations already served by the grid. The most attractive POIs are locations with an existing large conventional power plant—generally a coal-fired or nuclear plant. Several of these are shown in Figure 19; some are scheduled to be retired over the next few years and some are expected to continue operating for an extended period. Most of the plants identified are located near Lake Michigan, Lake Erie, and Lake Ontario—consistent with higher regional population densities and electricity demand relative to those near Lake Huron and Lake Superior. Key questions to address include:

- How much additional capacity—offshore wind or other—can the system accommodate in its current state?
- Which plants are scheduled to retire, and when?
- How much additional new capacity would these retirements allow?
- What new transmission capacity, both planned and not currently under consideration, could be added to increase the region's capacity to accommodate additional offshore wind energy expansion in the Great Lakes?

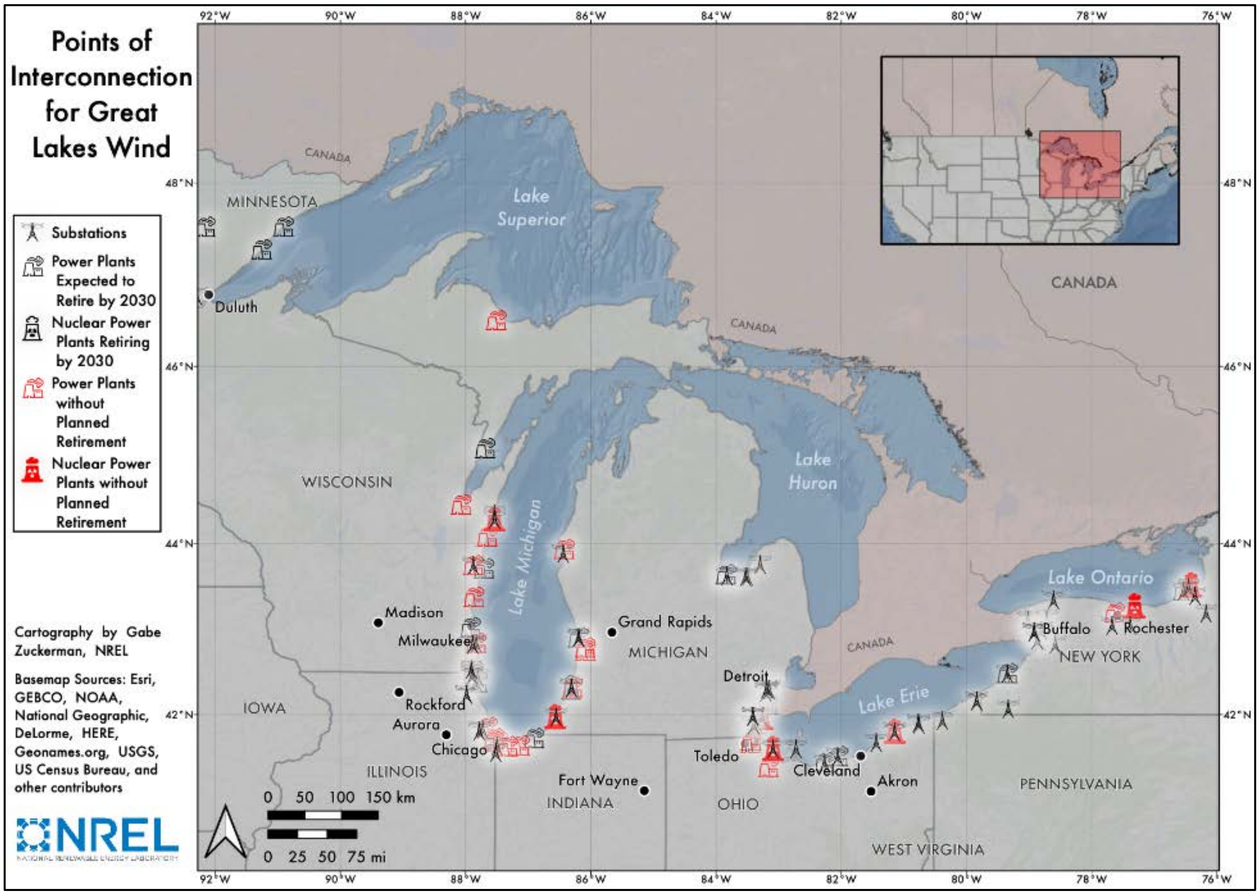


Figure 19. Potential points of interconnection for Great Lakes wind energy. ***Image from NREL***

In addition to addressing electric grid interconnection issues and prospects, the installation, maintenance, and integrity of electric cabling associated with a Great Lakes wind power plant and its connection to a land-based POI require careful consideration. Key questions include:

- Are the needed cable-laying vessels readily available on the lakes or can they be brought in through existing locks?
- How significant are icing issues to high-voltage cables, from the wind turbine connection to landfall?
- Will cabling require special armoring or other mechanical protection measures to deal with icing interactions?

6.2 Key Challenges

6.2.1 Evaluate POIs and Transmission Needs

Priority	Major Deployment Barrier	High-Cost Impact	Impacts All Lakes	Level of Knowledge
2	No	Yes	Yes	Medium

Description. The amount of Great Lakes wind capacity that can be accommodated by the regional electric networks depends on:

- Locations of suitable POIs to the land-based network
- Available capacities at plausible POIs
- Available transmission capacities from these locations
- Land availability for the extension of existing substations
- Planned or potential upgrades to transmission assets and associated rights of way
- Expected retirements of existing power plants
- Impacts of injections of offshore wind on electric system reliability
- Degree of correlation of offshore wind resource with electricity load profiles
- Interactions with other planned clean energy projects
- Variable renewable energy options for storage and grid flexibility
- Interconnection process
- Cost allocation for required transmission upgrades
- Possible constraints on siting and transmitting land-based wind and solar energy projects
- Possible interstate transmission through the lakes to serve major load centers and relieve congestion.

Four independent system operators/regional transmission operators have jurisdiction over Great Lakes offshore wind energy—three in the United States and one in Canada. MISO and Canada's Independent Electricity System Operator (IESO) share control of the grid in and around Lake Superior and Lake Huron. MISO and PJM share control of the grid in and around Lake Michigan; IESO, NYISO, and PJM share control in and around Lake Erie; and IESO and NYISO share control in and around Lake Ontario (Figure 20).

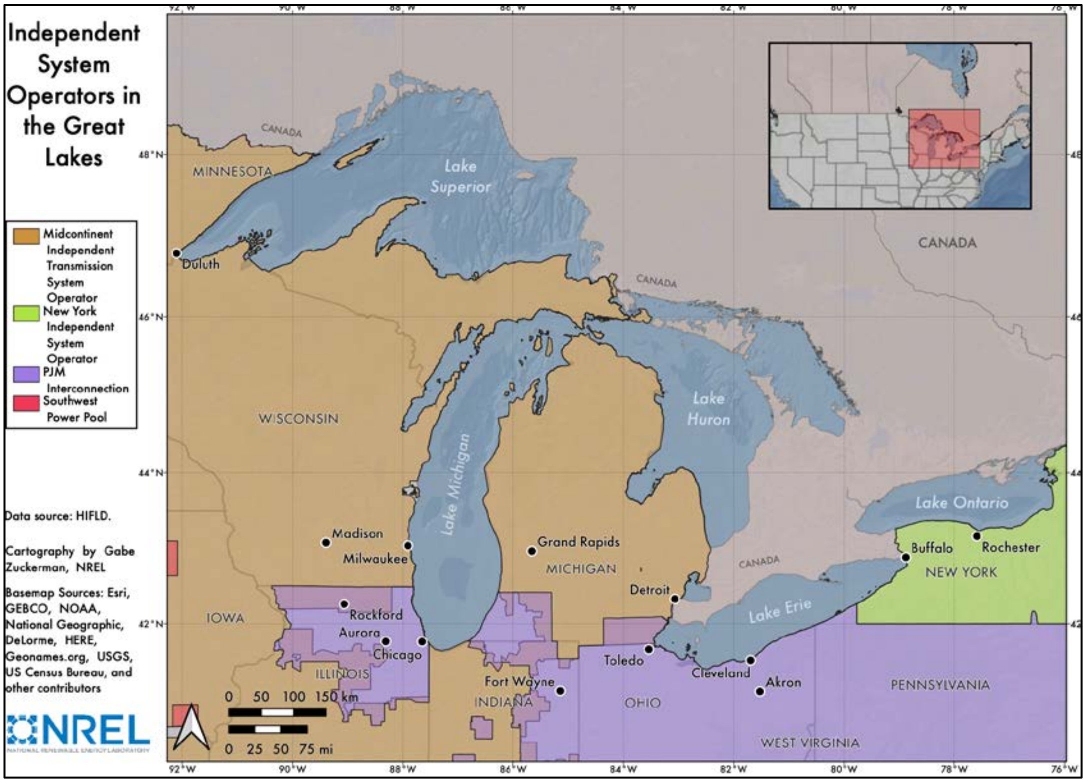


Figure 20. MISO, NYISO, PJM, and Canada's IESO plan and operate the power system around the Great Lakes. ***Image from NREL***

Quantifying interconnection opportunities is a complex task that can only be successfully accomplished by performing comprehensive analyses such as power flow and contingency modeling, production cost modeling, and system stability assessments. High-level analyses performed in this report (not based on detailed power system simulations) only apply as a preliminary screening step, but do not allow any engagement in terms of defining POIs for real investments.

Few Great Lakes wind energy transmission studies have been published. Below are summaries of the key studies.

Lake Erie (PJM)

A 2016 study for DOE (Sajadi et al. 2016) identified technical challenges and planning requirements related to integrating 1 GW of offshore wind energy on Lake Erie in PJM. Steady-state contingency analysis, small signal stability analysis, and large signal analysis were performed in the study, which considered the following scenarios with plausible POIs at the Perry 345-kilovolt (kV), Avan 345-kV, Lakeshore 138-kV, Eastlake 345-kV, and Ashtabula 138-kV substations:

- Interconnecting 1,000 MW of offshore wind generation at the Perry 345-kV substation
- Interconnecting five 200-MW cables of offshore wind generation at the Avon 345-kV substation, Lakeshore 138-kV substation, Eastlake 345-kV substation, Perry 345-kV substation, and Ashtabula 138-kV substation

- Interconnecting two 500-MW cables of offshore wind generation at the Avon 345-kV substation and Lake Shore 138-kV substation.

Among other findings, this study concluded that integrating 1 GW of offshore wind energy:

- Could improve voltage regulation across the system
- Did not degrade the critical clearing time following a short-term fault with successful clearance
- Led to improved frequency response of the system following long-term faults
- Improved the short-term transient voltage stability of the system
- Did not affect the long-term transient voltage stability of the system.

Several years later, the Lake Erie Interconnector study (PJM Interconnection 2013, 2018, 2019) evaluated bringing Canadian renewable energy, including hydropower, to help meet demand in PJM. It is plausible that 1 GW of Great Lakes wind energy could be interconnected at either the Erie West 345-kV substation or the Erie East 345-kV substation (not additive), in Erie County, Pennsylvania, with estimates of onshore upgrades of $30 million or more.

Lake Erie (NYISO)

The recent Pterra study for NYSERDA shows that for NYISO and Lake Erie, the available POIs have nearly zero headroom capacity without transmission upgrades (NYSERDA 2022a). Congestion along the transmission path from the Lake Erie POIs to the load centers downstate limit the number of megawatts that can be interconnected. Dunkirk 230-kV, Ashville 115-kV, Stolle Rd 230-kV, and Elm St 230-kV substations each have a solo headroom capacity of 10 MW without transmission upgrades. Transmission upgrades to address the congestion would permit some 100 MW to be interconnected at each of these four POIs for approximately $27 million each.

Moreover, the NYISO network around Lake Erie consists mainly of 115-kV lines and substations that are near the end of their service life and therefore are likely to require (and/or undergo) upgrades in the coming years.

Lake Ontario (NYISO)

For Lake Ontario, several POIs (Pannell 345 kV, Rochester 345 kV, Clay 345 kV, and Oswego 345 kV) in Monroe and Oswego counties showed simultaneous headroom capacities in the range of 850−1,100 MW without the need for transmission upgrades. At most, up to 1,140 MW of total Lake Ontario Great Lakes wind energy generation can be interconnected. POIs in Niagara County (Somerset 345 kV and Robinson Rd 230 kV) offer headroom capacity of up to 250 MW and 100 MW, respectively, if upgrades of $21 million are implemented. The POIs (Fort Drum 115 kV and West Adams 115 kV) tested in Jefferson have zero headroom capacity and require substantial investments in transmission upgrades to obtain slight increases in the headroom.

Lake Superior, Lake Michigan, and Lake Huron (MISO)

According to MISO short- and midterm transmission capacity assessments, the northern area of the MISO system, including around the Great Lakes, is heavily congested in the 5-year-ahead period of analysis. Figure 21 shows the current capacity, all of which is negative (orange colors) for more than 100 miles surrounding the Great Lakes, indicating that this region of transmission is heavily congested. Injections of Great Lakes wind energy in these regions would require significant, onshore, high-voltage transmission upgrades and/or thermal power plant retirements. Moreover, there are several other renewable energy projects in the interconnection queue in this region of the MISO network that will compete for POIs with Great Lakes wind energy.

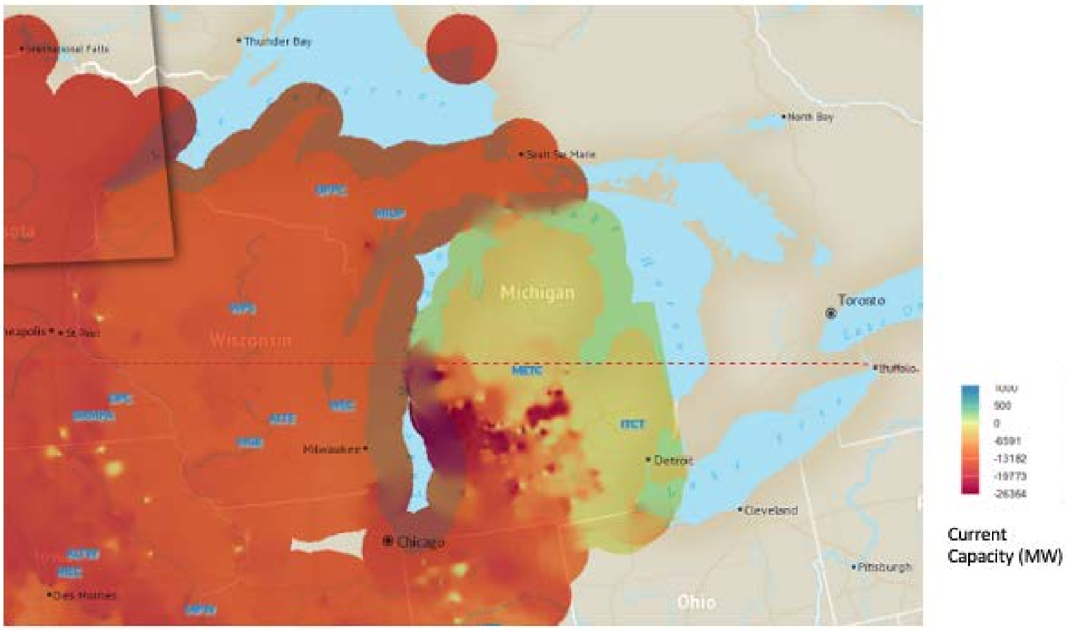


Figure 21. The MISO point of interconnection tool shows the current capacity of transmission lines in its region. ***Image from the [MISO point of interconnection tool](#)***

Consequences and impact. The transmission grid around the Great Lakes is not strong, therefore substantial upgrades would be needed to inject significant capacities of wind energy. Evaluating the needs for upgrades and determining the optimal locations, types, and capacities of upgrades would prevent delays to deploying Great Lakes wind energy.

Performing capacity expansion modeling would inform the optimal size and locations of offshore wind power plants. Production cost modeling would quantify key performance indicators including system production costs; capacity value; transmission interface flows and congestion hours; wholesale prices; curtailment levels; and system ramping needs. Power flow and system stability studies would test reliability and resilience under nominal and high-stress periods.

Recommended research activities include:

- Identifying prospective POIs and determining available headroom allowed by existing and already planned transmission capacity (level of effort: $200,000−$500,000, timeline: 6 months–1 year)
- Identifying fossil-fuel plant locations and capacities and estimating retirement timing; estimating released transmission capacities and impacts on headroom (level of effort: $200,000−$500,000, timeline: 1–3 years)
- Estimating potentials for acceleration of retirements enabled by offshore wind energy additions (level of effort: $200,000−$500,000, timeline: 1–3 years)

- Identifying planned transmission upgrades and estimating impacts on headroom capacities (level of effort: $200,000−$500,000, timeline: 1–3 years)
- Studying of retirement scenarios by systems operators (level of effort: $200,000−$500,000, timeline: 1–3 years)
- Analyzing potential for additional transmission upgrades not currently planned and estimating headroom capacity impacts including potential lake-based transmission backbones to relieve congestion (level of effort: $1 million−$2 million, timeline: 1–3 years)
- Conducting comprehensive grid integration analysis to study the impacts of the previously mentioned items holistically on the opportunities of Great Lakes wind energy additions to the regional grids (level of effort: >$2 million, timeline: 3−5 years).

6.2.2 Assess Cable Design, Installation, and Maintenance

Priority	Major Deployment Barrier	High-Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Cable installation requires suitable vessels for cable laying, burial, repair, and shore landings. The availability and physical sizes of these vessels need to be assessed. A full inventory will determine if such vessels exist in the Great Lakes and what limitations are imposed by the locks or other constraints. Once installed, cables will be exposed to icing conditions, including ice sheets and ice ridges. These conditions can lead to both mechanical loading and scouring—where cables emerge from the water, and at shallow locations along the lakebed where the bottoms of ice ridges may compromise cables. Because freshwater ice is stronger than sea ice, it can deliver a larger impact before buckling (Timco and Frederking 1982).

Power cable failure is a prominent risk for any offshore wind energy equipment. The impacts of icing on cable integrity, wear and tear, and cable maintenance need to be understood better and managed. Existing submarine cables could serve as useful case studies. The same idea applies to substations, wherein fixed-bottom or floating technology needs to withstand the effects of possible ice interactions while maintaining the electrical integrity of the system. This challenge is especially relevant for understanding what is necessary to protect the dynamic cables on a floating wind turbine or floating substations from damage due to ice floes. The challenge is compounded by the reality that sea-based offshore wind energy provides little relevant experience with these issues.

Consequences and impact. If cable laying or icing presents major challenges that are not discovered until after significant resources have been invested in an offshore wind energy project on the lakes, that investment could be lost. Alternatively, the costs of overcoming those challenges could be much higher than the cost of evaluating and addressing them in the early stages of the project. As a result, this research will allow for a better understanding of the relative importance of cable issues. Furthermore, project developers will be able to allocate an appropriate level of project resources to cable laying, connections, and maintenance. Design of the cables, substations, and electrical connection facilities will be influenced to minimize icing issues.

Recommended research activities include:

- Identifying requirements for laying cable—both intra-array and export cables from the array to the land-based POI; consider both lake-floor cables for fixed-bottom wind turbines and dynamic cabling for floating turbines. Determine if suitable cable-laying vessels are available on the lakes and transportable through existing locks. Determine limitations on cable installation imposed by lock sizes, both within the lakes and from the Atlantic Ocean (level of effort: $1 million−$2 million, timeline: 1–3 years)
- Examining potential effects of icing and ice scouring on cables where they emerge for connection to land-based POIs (shore landings) and to wind turbines and substations; assessing mitigation approaches, such as the connection below the waterline; developing cable routing plans to minimize potential ice effects and hazards (level of effort: $500,000−$1 million, timeline: 1−3 years)
- Developing design mitigation strategies to protect dynamic cables, array cables, and high-voltage export cables in floating wind turbines systems from potential damage from various ice impacts and determining how cables should be protected to withstand those impacts. This activity should consider cable protection at shore landings in particular, and cables to and from fixed and floating substations (level of effort: $1 million−$2 million, timeline: 3–5 years).

6.2.3 Assess and Compare High-Voltage Alternating Current vs. High-Voltage Direct Current Transmission Technologies

Priority	Major Deployment Barrier	High-Cost Impact	Impacts All Lakes	Level of Knowledge
2	No	Yes	Yes	Medium

Historical transmission experience suggests that typical line lengths in the Great Lakes would not be long enough to justify using high-voltage direct current (HVDC). However, engineering judgment on this issue is evolving as the costs of HVDC components and switchgear continue to fall.

While many offshore wind energy plants use high-voltage alternating current (HVAC), using it for offshore wind power plants has decreased in recent years because of the high loss of electricity due to reactive power, which increases with cable length and voltage squared. Reactive power compensation units can be installed along the cables, but this is difficult and expensive. A comparison of HVAC, line commutated converter (LCC)-HVDC, and voltage source converter (VSC)-HVDC for a 400-MW offshore wind power plant found that the cost for HVAC increases substantially for distances greater than 150 km (Figure 22) and that the cost of LCC-HVDC is the cheapest of the three systems at distances greater than 52 km (see Figure 23). The cost of VSC-HVDC is cheaper than HVAC for distances greater than 85 km. This study used a model that does not account for installation costs and onshore upgrade costs. The installation cost for the LCC-HVDC platform is substantially higher than the installation cost for the VSC-HVDC platform because the LCC-HVDC platform is much larger. Moreover, LCC-HVDC technology presents technical limitations for applications using underground or subsea cables.

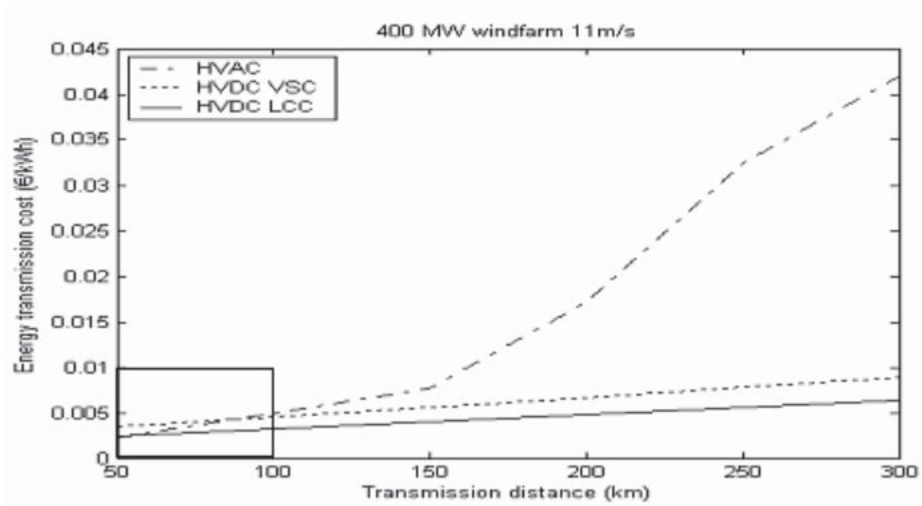


Figure 22. Energy transmission cost for a 400-MW wind power plant and 11-m/s wind speed for distances between 50 and 300 km. ***Image from Reed et al. (2013)***

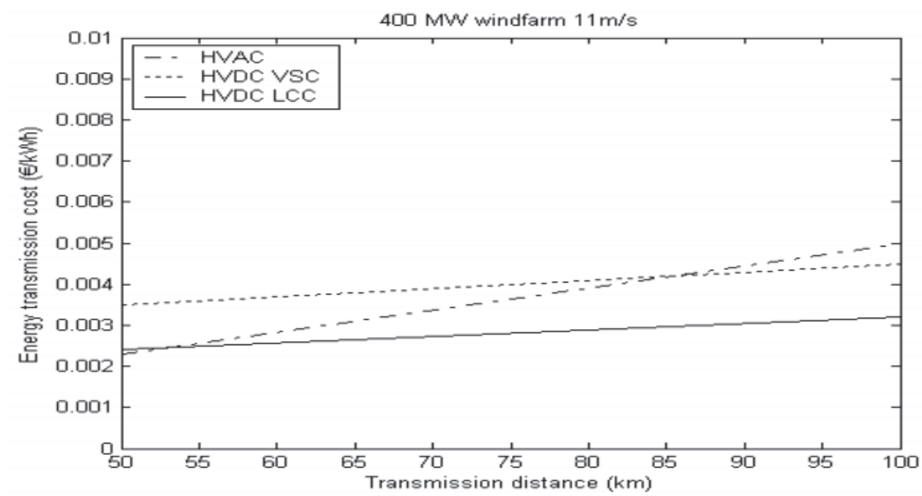


Figure 23. Energy transmission cost from Figure 22 magnified for 50–100 km. ***Image from Reed et al. (2013)***

NREL has developed the Offshore Renewables Balance-of-system and Installation Tool (ORBIT) to calculate the cost of transmission for offshore wind plants. Figure 24 shows cable design, cable installation, offshore substation design, and offshore substation installation costs calculated by ORBIT. The onshore cost assumes the minimum cost of interconnection, which includes the additional substation hardware required at an onshore substation. For HVAC, this includes switchgear and a transformer; for HVDC, it includes a DC breaker, an AC/DC converter, and a transformer. A risk contingency cost is included, estimated at 8% of the sum of all other project costs (Tabrizi et al. 2020). Figure 24 includes a breakdown of some component costs that are inputs to ORBIT.

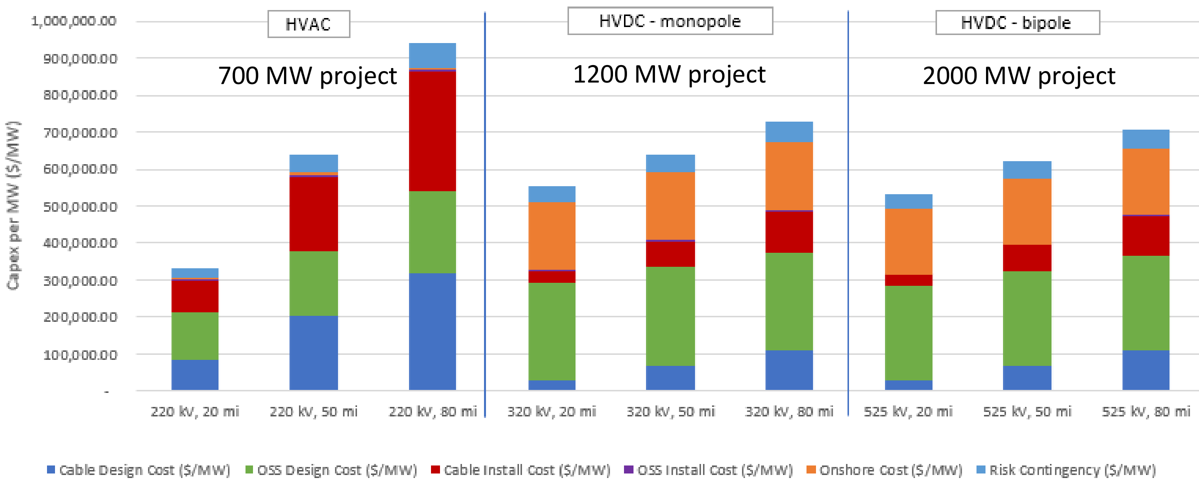


Figure 24. Cost metrics calculated by NREL's ORBIT model. ***Image from NREL***

Note: Capex = capital expenditures, OSS = Offshore Substation

Consequences and impact. The optimal transmission solution, including choosing HVAC and/or HVDC, as well as the topology, must be carefully studied to evaluate costs, reliability, and resilience. Without careful evaluation, the cost of Great Lakes wind energy could be unnecessarily high. Whether HVAC and/or HVDC is preferable for a given project or set of projects is a question that must be addressed for all offshore wind energy, whether in the Great Lakes or elsewhere.

Recommended research activities include:

- Assessing relative benefits and risks of HVAC and HVDC for interconnection between Great Lakes wind energy plants and land-based substations; estimating cable lengths beyond which HVDC becomes preferred. This evaluation should be conducted in conjunction with similar studies for sea-based offshore wind, with particular attention to any relevant differences between seawater and fresh water or in icing conditions because the need for this assessment is not unique to the Great Lakes (level of effort: $500,000−$1 million, timeline: 1−3 years)
- Identifying HVDC standards that apply to the Great Lakes; examining interoperability between HVDC and HVAC equipment; assessing the potential role of HVDC in the Great Lakes (level of effort: $500,000−$1 million, timeline: 3–5 years).

6.2.4 Examine Additional Grid Opportunities

Priority	Major Deployment Barrier	High-Cost Impact	Impacts All Lakes	Level of Knowledge
3	No	No	Yes	Medium

In addition to producing domestic electric power, opportunities may exist for cooperative development or off-taking with Canadian entities. In addition, it may be possible and even advantageous to produce green hydrogen or other clean fuels from Great Lakes wind energy. These longer-term opportunities may become critically important elements of the nation's long-term strategy (The White House 2021) as the nation advances from 100% clean electricity in

2035 to zero greenhouse gas emissions by 2050. As such, these options need to be examined, since they could materially influence the design, installation, and operation of Great Lakes wind energy facilities. Impacts on transmission requirements could be substantial.

Consequences and impact. Prospective attractive opportunities to lower grid integration costs and integrate Great Lake wind energy might be ignored but might be needed to help states meet their carbon reduction targets. Early-stage developers are unlikely to give serious consideration to these potential systemwide opportunities in the near term. Examination of these opportunities with public funds could accelerate pursuit of such options and inform long-term state planning.

Recommended research activities include:

- Conducting research to examine opportunities for Canadian cooperation, including additional markets for offshore wind energy, synergies with Canadian hydropower, and joint development of interconnection facilities, among others (level of effort: $500,000–$1 million, timeline: 6 months–1 year)
- Conducting research to examine opportunities for Great Lakes offshore wind plants to produce green hydrogen or other clean fuels in addition to, or instead of, electricity; assessing related impacts on transmission requirements (level of effort: $1 million–$2 million, timeline: 3–5 years).

7 Environment and Wildlife

7.1 Current Situation

The Great Lakes region is home to an abundance of wildlife that rely on healthy waters and intact habitat for survival (The National Wildlife Federation undated). The potential effects of Great Lakes wind energy activities on wildlife, habitat, and ecosystems need to be appropriately assessed and mitigated as early as possible in the planning process. Compliance with relevant federal and state environmental laws (e.g., NEPA, Endangered Species Act [ESA], Migratory Bird Treaty Act [MBTA], and the Bald and Golden Eagle Protection Act [BGEPA]) requires significant planning and assessment and can delay the wind energy development process when gaps are identified. The important role of environmental considerations in the consenting process leads to a clear need to reduce environmental impacts through objective, scientifically sound research and development of mitigation strategies to help ensure that the benefits of wind energy projects outweigh the challenges.

The Great Lakes region provides important breeding and foraging habitat for resident species. In addition, the Atlantic and Mississippi Flyways pass over the Great Lakes, bringing millions of birds and bats to the region during spring and autumn migration (Figure 25). Bird species that reside or traverse the region include songbirds (e.g., black-poll warbler, red-eyed vireo), raptors (e.g., bald eagles, peregrine falcons), shorebirds (e.g., black terns, black-bellied plover), and waterfowl (e.g., horned grebe, hooded merganser).

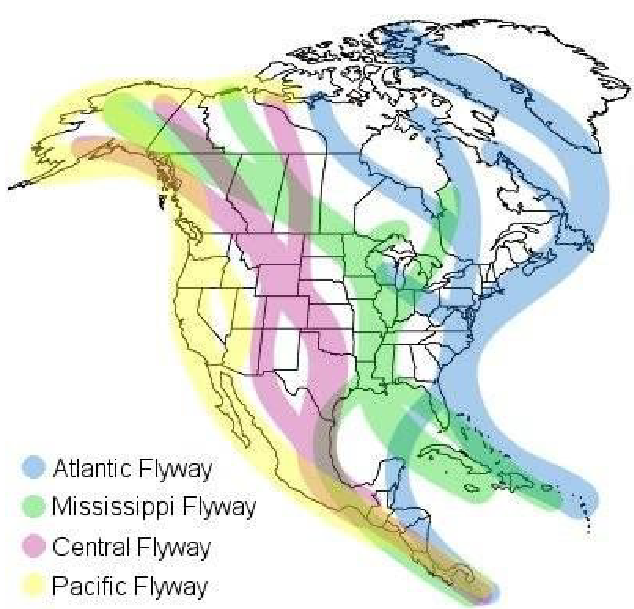


Figure 25. Main flyways for migrating birds in North America. ***Image from Audubon***

Regulatory protections for these species include the ESA, MBTA, and BGEPA. Eight species of bats inhabit the region, including three migratory tree-roosting species and five cave-roosting species. Currently, the Indiana bat (*Myotis sodalis*) and the northern long-eared bat (*Myotis septentrionalis*) are listed as federally endangered. The tricolored bat (*Perimyotis subflavus*) is proposed for listing as endangered, and the little brown bat (*Myotis lucifugus*) is being considered for listing by the U.S. Fish and Wildlife Service (FWS).

There is uncertainty regarding how resident and migratory bird and bat species will interact with Great Lakes wind energy. Interactions may include attraction, which may increase the risk of collisions, or displacement or avoidance, or attraction, which may have indirect effects on energetics and survival. Inferences can be drawn based on overall activity in the region and from studies conducted at land-based wind energy facilities. Several acoustic and radar studies have documented high activity and use along the shorelines of the Great Lakes (FWS undated). These results show that the concentration of migrants (both birds and bats) differs between spring and autumn migration (Figures 26−27). Furthermore, many of the species that use the area have experienced fatalities at land-based wind energy facilities in the region. Yet, it remains unclear whether wind turbines in the Great Lakes represent a significant risk (as defined by the FWS's *Land-Based Wind Energy Guidelines* [2012]). Part of this uncertainty is because there are limited publicly available mortality data from wind energy facilities near the Great Lakes. Access to these data may inform how mortality changes among facilities relative to proximity to the shoreline. Regardless, additional information is necessary to quantify flight patterns (e.g., flight height, passage rate, weather conditions) of migrants flying over the Great Lakes. Data are also needed to understand how bats and birds behave (i.e., approach and interact or avoid) in response to the presence of wind turbines sited on the water and how interactions may change under different weather and temporal conditions. These data can be used to inform siting decisions to avoid risk, and potential strategies to minimize risk during operation.

Figure 26. For the spring migration season, consistently high concentrations of bird and bat migrants (in blue) occur along the western edge of the Great Lakes basin. *Image from FWS*

Note: Warmer colors at the center and eastern edge of the basin indicate lower migrant concentrations and greater variation in the number of migrants passing through each night during the season.

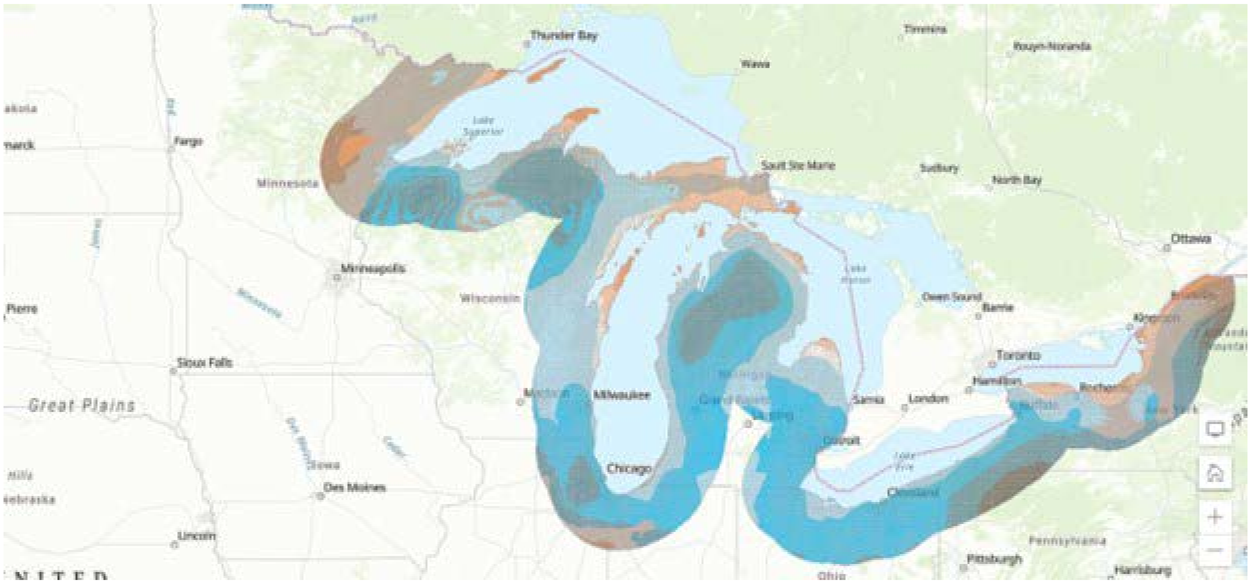


Figure 27. For the fall migration season, consistently high concentrations of bird and bat migrants (in blue) occur along the south-central edge of the Great Lakes basin. ***Image from FWS***

Note: Warmer colors along the eastern and western edges and the center of the basin indicate lower migrant concentrations and greater variation in the number of migrants passing through each night during the season.

Numerous fish and invertebrate species also rely on the Great Lakes for habitat, including 139 native fish species and numerous non-native fish species (Great Lakes Fisheries Commission [GLFC] 2022). There is notable variability in the fish and aquatic wildlife amongst the Great Lakes, based on the wide range in lake characteristics ranging from the cold, deep conditions of Lake Superior to the warmer, shallower conditions of Lake Erie. Some examples of fish species found in the region include walleye, yellow perch, lake sturgeon, brook trout, lake whitefish, muskellunge, and introduced salmon species, with some species undergoing restoration efforts. Endangered species in the region include various types of clams, crustaceans, fish, and snails. According to the GLFC (2022), 61 fish species in the Great Lakes are considered to be threatened or endangered. A federal court has ordered the FWS to make a determination by 2024 on whether imperiled populations of lake sturgeon will be protected under the ESA (Center for Biological Diversity 2021). Over time, the fish fauna of the lakes has been altered due to increasing human populations, overfishing, and a rise in the introduction and spread of invasive species.

The long history of human reliance on the Great Lakes has led to environmental concerns and degradation that need to be considered for any future development activities, including offshore wind energy. Pollution is a threat in the region because of the various sources of toxic pollutants and persistence of chemicals in the environment for many years, with effects on food webs and ecosystems. Climate change is already being observed in the Great Lakes in the form of increasing air and water temperatures, leading to increased evaporation, shifts in lake levels, and worsened water quality. In addition, the spread of invasive species has significantly changed the region by threatening native species and causing harm to fisheries, as well as other impacts. Additional offshore structures, including wind turbine foundations, could potentially act as stepping stones for invasive species, and this should be considered to minimize spread of these organisms. With relevance to Great Lakes wind energy development, appropriate assessment and mitigations need to be developed to minimize exacerbation of these existing threats. On the other hand, responsible renewable energy deployment is an effective strategy for combating the effects of climate change, so this benefit needs to be part of a balanced risk assessment. Offset mitigation may also be of value for reducing impacts of existing threats, such as invasive species and contamination.

Given the early stage of Great Lakes wind energy, there is an opportunity to incorporate lessons learned from other regions and past experiences with initial projects in the lakes. For example, through the DOE-funded SEER project, NREL and PNNL summarized effects on the U.S. Pacific and Atlantic coasts related to noise, entanglement, emplacement of structures, electromagnetic fields (EMFs), birds/bats, benthic disturbance, and vessel collisions. Specific to the Great Lakes, the Michigan Great Lakes Wind Council (2010) included biological and habitat criteria while defining the most favorable lease areas. In 2018, the LEEDCo IceBreaker project in Lake Erie completed its environmental assessment process for sensitive resources (DOE 2018a). More recently, the *New York Great Lakes Wind Feasibility Study* included an analysis of environmental relative risks and minimization/mitigation measures (NYSERDA 2022a). In addition, PNNL and the U.S. Geological Survey are developing a buoy-based radar system to detect birds and bats over open water and demonstrating its performance by collecting preconstruction monitoring data in the Great Lakes.

7.2 Key Challenges

7.2.1 Address Great Lakes Uncertainties in Bat and Bird Interactions With Wind Turbines

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. The Great Lakes region supports a relatively high concentration of bats and birds traversing the central and eastern flyways during spring and autumn migration (Heist et al. 2018). Eight species of bats are known to occur within the region, including three migratory tree-roosting species (hoary bat [*Lasiurus cinereus]*, eastern red bat [*Lasiurus borealis*], and silver-haired bat [*Lasionycteris noctivagans*]), that account for nearly 72% of reported fatalities at wind turbines (Dzal et al. 2009; American Wind Wildlife Institute 2020). Cave-hibernating species, such as the Indiana bat, also occur in the region and have been decimated by white-nose syndrome. Several of these species are federally listed as endangered (i.e., Indiana bat and northern long-eared bat). Nearly 200 species of songbirds, waterfowl, raptors, and shorebirds migrate across the region (Audubon Great Lakes 2022). Most of these species are protected under the MBTA, ESA, and BGEPA.

Quantifying use, including breeding, foraging, and migrating, by birds and bats in the region has relied on a variety of technologies including radar (Cohen et al. 2022), acoustic detectors (Stantec 2016), banding (Sanders and Mennill 2014), radio telemetry (McGuire et al. 2012) and geographical information systems (Audubon Great Lakes 2022). To date, most studies have been conducted along the shorelines, with a few taking advantage of small islands within the lakes (Sanders and Mennill 2014). These studies have indicated that movement along the shoreline varies by geography and timing (Cohen et al. 2022). However, there are limited data on which species cross the Great Lakes, the flight altitude, how weather patterns influence passage rates, and whether the presence of wind turbines will detrimentally alter behavior.

Consequences and impact. The impacts of wind turbines on some species of birds and bats may contribute, along with other stressors, to population-level declines (Rosenberg et al. 2019; Cheng et al. 2021; Friedenberg and Frick 2021). The additional mortality for federally- and state-listed species may hinder recovery. Moreover, the regulatory status of many species within the region will likely result in the need for permits, and/or delay or prohibit Great Lakes wind energy development. To expedite this development, DOE can support technology development to address the research gaps associated with baseline activity and movement patterns, behavioral responses to wind turbines, mortality monitoring, and if necessary, minimization strategies.

A combination of baseline and postconstruction studies are necessary to determine the activity patterns of bat and bird movement across the Great Lakes. Below are some recommended research activities, with suggested timelines and funding effort, that may help address the uncertainty surrounding bird and bat interactions with Great Lakes wind energy. These recommendations are not intended to replace federal or state guidance for monitoring.

Recommended research activities include:

- Monitoring baseline activity patterns relative to time (e.g., nightly, seasonally), space (e.g., distance from shore, flight height), and weather (e.g., wind speed, temperature) of bats and birds flying over the Great Lakes. A minimum of 2 years of monitoring, prior to construction, may be required to quantify patterns. Ideally, all five of the Great Lakes will be monitored simultaneously to account for spatial and temporal variation under baseline conditions, but priority is needed where development is likely to occur first (level of effort: >$2 million, timeline: 2−5 years).
- Developing and validating strike detection systems. Validating systems will require comparing results to standard postconstruction monitoring at land-based wind energy facilities. This comparison can be accomplished prior to constructing wind turbines on the Great Lakes (level of effort: >$2 million, timeline 1−3 years).
- Conducting postconstruction monitoring to quantify fatality rates of bats and birds. Validated strike detection systems can be installed on wind turbines to monitor fatality rates over multiple years (level of effort: $1−$2 million, timeline: 1−3 years).
- Assessing the turbine- and landscape-level behavior of bats (i.e., attraction) and birds (i.e., avoidance or attraction) in response to wind turbines on the Great Lakes. A minimum of 2 years is required to monitor behavior using one or more technologies (e.g., radar, cameras, lidar, and acoustic detectors). The technology or suite of technologies used will vary by development phase and scale of behavior. Behavior can be related to timing and weather conditions to understand how animals respond to the presence of wind turbines (level of effort: $1−$2 million, timeline: 1−3 years).

7.2.2 Assess Effects on Fish Ecology and Aquatic Resources (Native and Invasive)

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	No	Yes	Medium

Description. The Great Lakes support a productive and highly valued ecosystem of fish and invertebrate species. According to the GLFC (2022), there are over 177 fish species in the Great Lakes, including both native and non-native species. Examples of native species include top predators, forage species, lamprey species, and invertebrates, such as mussels and clams. Alterations have occurred in the fish fauna due to human impacts on the environment, including from overfishing, which has led to the extirpation of some species, and 61 fish species in the Great Lakes are now considered to be threatened or endangered (GLFC 2022). Non-native invasive species also proliferate in the Great Lakes, including sea lamprey and quagga mussels, and can cause harm to the ecosystem and disruption of native fish populations through competition for food and habitat or predation (EPA 2022b).

There are several stressors associated with offshore wind energy development that can potentially affect fish and invertebrate ecology, including sound/particle motion, bottom disturbance (such as from scour protection), placement of structures, alteration of habitat, and EMF (e.g., GLWC 2011b, 2013). Great Lakes wind energy planning efforts have identified potential impacts on fish species as an important consideration in the siting process (e.g., GLWC 2009). The Michigan Great Lakes Wind Council (2010) identified the most favorable lease areas that were at least 6 miles offshore to avoid sensitive fish and wildlife habitats, shipping lanes, and other considerations. Avoidance of impacts on threatened and endangered species (including fish) and recreational fish spawning sites and refuges were also identified.

In Ohio, as part of Icebreaker's compliance with the NEPA process, a wildlife risk analysis was performed for fish and aquatic resources, including consideration of fish spawning or larval nursery areas, reefs, or shoals that offer enhanced fish habitat (LimnoTech 2017). Potential effects of EMF on fish were also considered, with the finding that "… the abundant current research showing that EMFs from transmission cables similar to the one proposed by LEEDCo do not have a significant effect on fish behavior" (DOE 2018a, b). As well, study of a wind power project submarine cable in Lake Ontario found limited influence on the fish community; however, it was recommended that more robust impact assessments would require sampling fishes prior to cable installation, over longer time frames, and in habitats that support more diverse native assemblages (Dunlop et al. 2016). In the New York State *Great Lakes Wind Energy Feasibility Study*, researchers assessed fish resource characteristics related to habitat zones, nearshore and offshore (pelagic and deep benthic) communities, migratory versus nonmigratory species, prey fish, endangered species, invasive species, and sea lamprey control (NYSERDA 2022a).

The generation of noise during impact-pile driving associated with the construction of offshore wind energy development could be a potential risk to fish species in the Great Lakes (e.g., Wisconsin Public Service Commission 2009). As noted previously, there are no marine mammals in the Great Lakes. The potential effects of noise/vibration on sensitive fish species may include injury/mortality, behavioral disturbance, and displacement. While marine fish with swim bladders have more potential to be injured by sound and particle motion than fish without swim bladders, less is known about the potential for freshwater fish in the Great Lakes with swim bladders to be impacted by sound and other disturbances. A recent study was performed on the black bullhead, a common species in the Laurentian Great Lakes with known hearing specializations and showed that sensitive freshwater fishes alter their foraging behavior during noise exposure (Pieniazek et al. 2020). Further study is needed to understand how variation in hearing abilities may determine the extent to which their behavior changes and the resulting degree of negative consequences. A variety of mitigation measures are available for reducing noise during offshore wind construction activities and could be considered for application in the Great Lakes (e.g., Bellmann et al. 2020).

Consequences and impact. Numerous fish and invertebrate species are threatened or endangered in the region and may be covered by federal and state ESA considerations (e.g., pugnose shiner, deepwater Sculpin, and Lake Sturgeon), which will be a factor in permitting for Great Lakes wind energy projects and could slow it down if required information is not available. DOE has the opportunity to fund research to better understand the potential impacts of wind energy development on native and invasive fish and invertebrate species in the Great Lakes, to build on existing research and partnerships in the region, and to advance regional goals specifically associated with offshore wind energy development.

Recommended research activities include:

- Collecting seasonal baseline data on sensitive fish and invertebrate species distributions and habitat in the regions of interest (level of effort: >$2 million, timeline: 3–5 years)
- Developing risk factor maps for key fish species, habitats, and spread of invasive species in relation to the potential impact from Great Lakes wind energy (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Assessing sensitivities of Great Lakes fish and forage species to noise/particle motion and EMF (level of effort: $1–$2 million, timeline: 1–3 years)
- Understanding how different wind turbine foundation designs could impact fish behavior and ecology in the region and assess mitigation measures (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Assessing the behavior of fish and other aquatic species at wind turbines and associated components in the Great Lakes (level of effort: $1–$2 million, timeline: 1–3 years)

7.2.3 Assess Ecosystem Effects of Various Environmental Stressors

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	No	Yes	Medium

Description. Ecosystem-based management has historically been an important consideration for offshore environmental work, including in the Great Lakes (e.g., Hartig et al. 1998; GLERL 2022b). The assessment of ecosystem-level effects from potential Great Lakes wind energy development requires an understanding of both the abiotic and biotic environmental impacts from associated activities, ranging from onshore to Great Lakes environmental stressors (e.g., Afsharian et al. 2020; GLWC 2013). For example, abiotic changes in water column mixing from Great Lakes wind energy development could have biotic impacts on the food chain, from introducing nutrients into the water column and increased primary productivity to eventually contributing to changes at higher trophic levels. Broader ecosystem-level considerations also include cumulative effects and how Great Lakes wind energy impacts the environment in addition to other stressors (GLWC 2013).

Multiple environmental stressors have been identified and studied in the Great Lakes that are relevant to considerations for wind energy development in this region. Models have been developed to forecast the impacts of these various multiple stressors (e.g., invasive species, climate, and nutrient cycling) on Great Lakes' water quality, food webs, and fisheries, and could be modified to evaluate and minimize the impacts of Great Lakes wind energy development (e.g., GLERL 2022b). Broadly, Great Lakes wind environmental research can build on the knowledge and efforts of existing Great Lakes research programs. For example, the Great Lakes Restoration Initiative (GLRI undated) and Great Lakes Commission (2022a) both include aspects of contaminants/toxic substances, water quality (e.g., harmful algal blooms), and invasives among their focus areas and could help inform related offshore wind energy research. Finally, cumulative impacts associated with Great Lakes wind energy development in addition to other stressors need to be assessed, including the documented impacts of climate change in the region (Environmental Law and Policy Center 2019).

Consequences and impact. Earlier approaches demonstrated limited success to managing the Great Lakes and mitigating anthropogenically induced stress, thus necessitating the adoption of a broader ecosystem approach. DOE has the opportunity to fund research that contributes to an ecosystem-based understanding of the potential environmental effects of Great Lakes wind energy development. Stakeholders are interested in environmental impacts that extend from offshore to onshore, and this research will encourage the impacts of multiple environmental stressors to be assessed. There is also the possibility that offshore wind structures in the lakes could be used to monitor water quality and perhaps also to improve/mitigate negative impacts from other stressors.

Recommended research activities include:

- Performing relative risk assessment of ecosystem-level effects from Great Lakes wind energy development across its lifecycle (e.g., from preconstruction to decommissioning) (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Advancing ecosystem models that can predict effects of new structures on aquatic species (native and invasive) and habitat (level of effort: $1–$2 million, timeline: 1–3 years)
- Understanding food web impacts—across trophic levels—of contaminants disturbed by Great Lakes wind energy activities (wind turbine and cable zone) (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Modeling potential changes to mixing, nutrients, and productivity due to wind turbine installation (level of effort: $500,000–$1 million, timeline: 1–3 years)

- Assessing cumulative environmental impacts of offshore wind energy development in addition to other stressors (e.g., climate change) (level of effort: $500,000–$1 million, timeline: 1–3 years).
- Identify how offshore wind structures in the lakes could be used to monitor water quality and ecological variables toward potentially improving/mitigating negative impacts from other stressors (level of effort: $200,000–$500,000, timeline: 6 months).

8 Human Use

8.1 Current Situation

The Great Lakes provide important resources and opportunities for millions of people. Approximately 34 million people in the United States and Canada live in the Great Lakes basin (Michigan Sea Grant 2022b), including coastal residents, tribes, and other user groups who prize their Great Lakes views and assets (Michigan Environmental Council 2006). The lakes contain about 90% of the fresh water in the United States and approximately 20% of the world's fresh water supply (NOAA 2019). Forty million people in the United States and Canada depend on the lakes for clean drinking water (roughly 10% of the U.S. population and 30% of the Canadian population). In 2019, the economy generated from maritime businesses that depend on the Great Lakes provided $10.2 billion in wages and contributed $21.5 billion in gross domestic product. Across sectors, tourism and recreation account for 75% of the employment and 56% of the total gross domestic product in the Great Lakes region (NOAA 2022).

Fisheries in the Great Lakes include sport, recreational, commercial, and tribal fishing activities (e.g., Hohman and Hayes 2021). In addition, recreational boaters, birders, beach goers, and tourists also utilize the beaches and waters of the Great Lakes. Moorings for personal boats are spread throughout the lakes, as well as wreck buoys that mark historical shipwrecks for safety and diving tourism. Buoys for meteorological observations are also deployed in spring, summer, and fall to support the Great Lakes Observing System[11] that shares biogeochemical and physical data from the lakes themselves.

Shipping lanes in the Great Lakes have been an important part of the region's economy since the late 1800s. More than 200 million tons of cargo pass through the Great Lakes each year and support industries that produce steel, chemicals, and other products (NOAA 2019). The St. Lawrence River and Great Lakes comprise the longest, deep-draft navigation system in the world. More than 100 ports and commercial docks are supported by these shipping routes in each of the bordering Great Lakes states, and are important for moving commerce between North America and overseas markets (English and Hackston 2013). Wind farms would need to be positioned to not interfere with shipping lanes.

Some of the main cultural services that the Great Lakes provide include tribal nations' activities, sportfishing, birding, recreational boating, use of beaches, and park visitation. The Great Lakes Environmental Assessment and Mapping Project used citizen science, agency reports, and social media to create a map of cumulative stressors (see Figure 28; NOAA 2023). The distribution of these ecosystem services can inform where conservation efforts should focus (Allan et al. 2015). For example, the results show that Lake Superior is the most remote of all the Great Lakes, whereas Lake Erie and Lake Ontario have the most cumulative stress from cultural ecosystem services. Note that further considerations for historical resources (e.g., shipwrecks) and tribes are discussed in Sections 9 and 11, respectively.

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[11] https://glos.org/

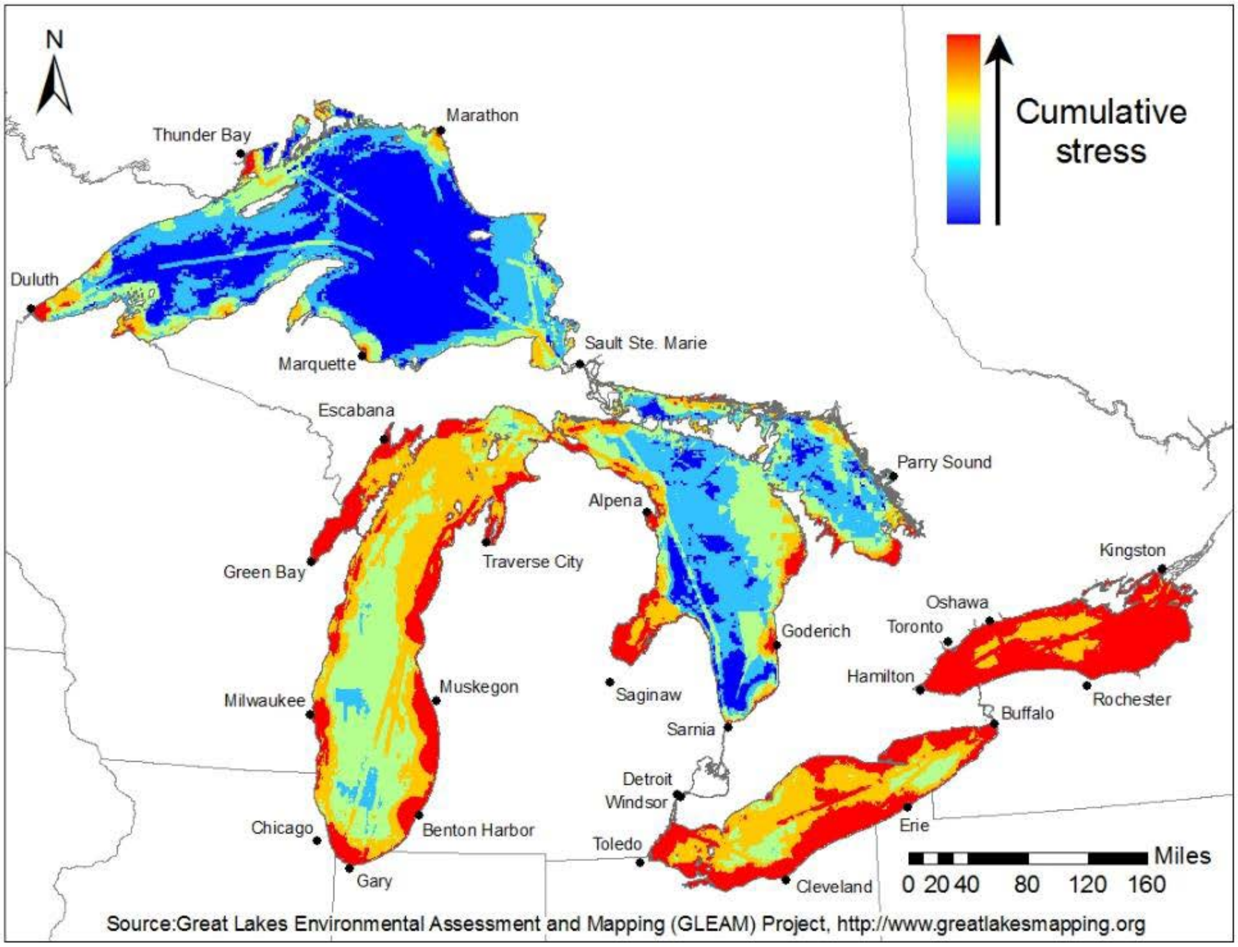

Figure 28. Cumulative stress from five cultural ecosystem services: recreational boating, birding, sportfishing, beach use, and park visitation. ***Image from the Great Lakes Environmental Assessment and Mapping Project. More information available in Allan et al. (2015)***

8.2 Key Challenges

8.2.1 Characterize and Address Viewshed Impacts

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	Yes	Yes	Medium

Description. Potential future Great Lakes wind energy projects may introduce visual impacts to states that border the lakes as well as Canada, which should be evaluated and addressed as part of any proposed development plan. In response to stakeholder interest regarding these visual impacts, viewshed analyses and visualization simulations have been important aspects of U.S. Atlantic development activities (e.g., Bureau of Ocean Energy Management 2015), as well as for LEEDCo and New York State in the Great Lakes (NYSERDA 2022a). In Michigan, part of the failure of the projects that Scandia proposed off the West Coast of Michigan's Lower Peninsula in 2010-2011 was driven by view-based opposition and aesthetics. Based on public feedback events and webinars, NYSERDA (2022b) identified viewshed impacts as one of the primary concerns associated with potential wind energy projects in and around the Great Lakes. Yet, there is the possibility for floating wind farms at a greater distance from shore to minimize visual impacts in deeper waters of the Great Lakes.

Preliminary viewshed analysis has been done for New York State in Lake Erie and Lake Ontario as part of the New York State *Great Lakes Wind Energy Feasibility Study* (NYSERDA 2022a). However, no formal sites, specific wind turbine designs, or wind power plant layouts have been assigned to use in New York State lake waters. Therefore, not only does viewshed analysis need to be completed on the other Great Lakes, but also a more traditional visual impact assessment using more specific wind plant setup needs to be done. This assessment includes identifying key points of observation, multiple height scenarios, and visual simulations.

Some tenants along the Great Lakes have already opposed offshore wind energy due to their perceptions about how their views will change. Overall, analyses need to evaluate how wind energy development could change the viewshed of people living, working, and recreating along the shorelines or offshore in the region. However, residents who live near polluting power plants also have concerns, which need to be considered and given weight when decisions are being made related to renewable energy siting and viewshed considerations for potential renewable energy projects.

Consequences and impact. Given the level of interest on this topic, the public and other stakeholders within the viewshed of the Great Lakes wind energy infrastructure may push back on project development if, for example, their property values will be affected, or aesthetic enjoyment of the lakes will be diminished. The strength of view-based opposition has implications for investment in technical solutions for fixed-bottom deployment in parts of the Great Lakes and may provide opportunities for floating wind farms that are further from shore. DOE investment will help to involve local communities and communicate the actual viewshed scenarios of potential Great Lakes wind energy projects, which can help to reduce uncertainty in the communities and aid in addressing problems. In addition, Canadians may have wind turbines in their viewshed, so an international approach to sharing viewshed simulations and information should also be taken. Concerns related to tribes and historical properties must also be considered.

Recommended research activities include:

- Identifying population centers and sensitive communities to viewshed concerns along shorelines. Develop strategies that also consider the concerns of property owners currently living near polluting power plants regarding the viewshed of offshore renewable energy projects (level of effort: \$200,000–\$500,000, timeline: 6 months–1 year)
- Collecting information on viewer sensitivity levels and concerns across the different activities of the viewers. Identify locations where view-based opposition would not be fatal to utility-scale proposals, with implications for whether fixed-bottom or floating technology is more applicable based on distance from shore (level of effort: \$200,000–\$500,000, timeline: 6 months–1 year)

- Conducting detailed regional assessments of visual impacts, considering an envelope of wind turbine dimensions and plant layouts (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Performing visual simulations from key observation points of potential Great Lakes wind energy projects, including meteorological conditions for different seasons and times of day, wind turbine sizes, and distances from shore. Present the results at public meetings (level of effort: $500,000–$1 million, timeline: 1–3 years).

8.2.2 Assess and Develop Avoidance and/or Mitigation for Drinking Water Impacts

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. Unlike the open ocean, Great Lakes freshwater resources are used by millions of residents in the region for their water supply. Water challenges have already occurred in the region, such as the water quality crisis that took place in Flint, Michigan, starting in 2014. It is essential that regional wind energy development does not in any way decrease the quality of the water supply. Ignoring or inadequately addressing concerns about how offshore wind energy development could negatively impact water quality could have consequences for both the public health and public opinion of offshore wind.

Although water utilities are able to manage high volumes of dredge spoil per year, the fact remains that there is uncertainty in where contaminants may lie and proper procedures must be evaluated and followed. This degradation could potentially come from several sources, including known contaminated sediment areas in the lakes, proximity to water intakes, and currents that transport sediments. Another source of potential contamination could be from resuspension or release of contaminated soils via dredging, and foundation and anchor installation procedures that could disturb the sediment layers. Dredging operations are routinely performed by the U.S. Army Corps of Engineers (USACE) to keep pathways clear and safe for navigation. In addition, USACE performs the initial excavation when a new channel is being developed. Permits are required for dredging and sediment testing may be required during the permitting process (Keil et al. 2022).

The tributaries of the Great Lakes are also a well-known pathway for pollutants, especially sediments laden with contaminants, to flow into the lakes (Adriaens et al. 2002). Therefore, higher concentrations of toxins could be expected in proximity to stream and river mouths. Because the level of sediment flux into the Great Lakes is a function of river flow and bed stability, any nearshore infrastructure developed near river mouths must consider effects to sediments and river flow.

The Great Lakes Restoration Initiative is a multiagency effort that provides funding to federal organizations with the goal of addressing the biggest threats to the Great Lakes ecosystem (GLRI undated). One primary focus of this initiative is to address toxic substances and areas of concern (Figure 29). This includes areas that might see illegal dumping from both the public and private sectors. In the *Great Lakes Restoration Initiative Action Plan III; Fiscal Year 2020 – Fiscal Year*

2024, a main goal is to increase knowledge about chemicals of international concern, as a follow up to the Great Lakes Water Quality Agreement's Annex 3 (GLRI 2019). Discrete monitoring of these harmful chemicals is currently being conducted and can inform what contaminants could be a potential issue while installing offshore wind infrastructure.

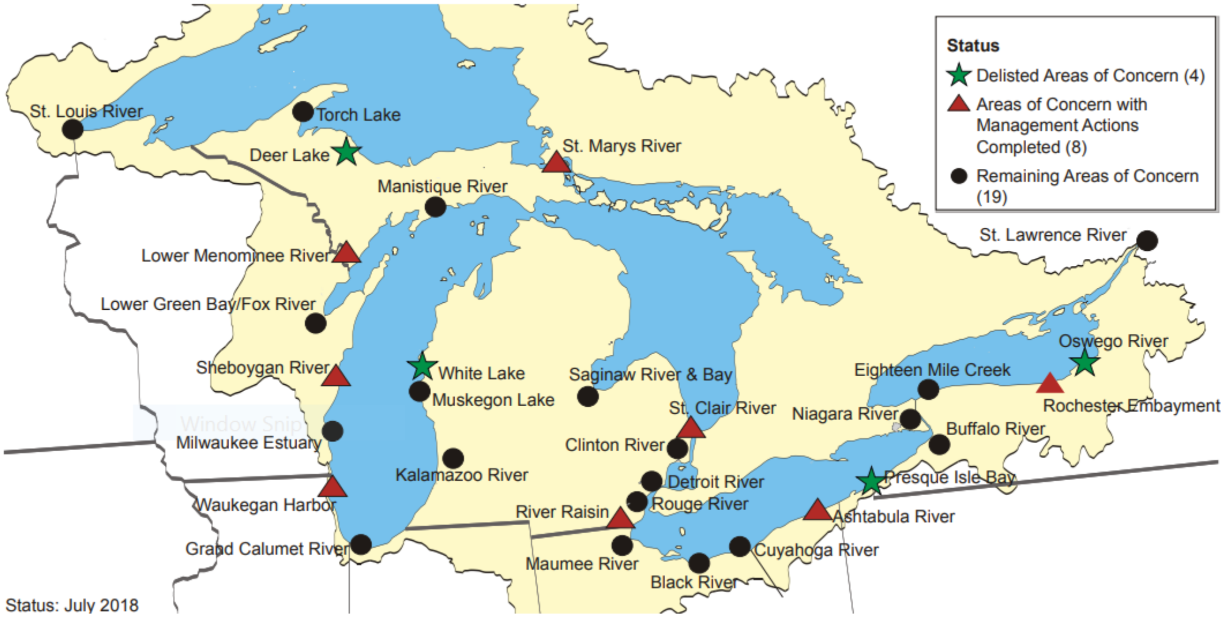

Figure 29. Areas of concern identified by GLRI (2019)

Consequences and impact. Improper siting could potentially contaminate drinking water due to the resuspension and spread of sediment contaminants, causing a public health hazard. It is important that any public safety issues not be overlooked, and that appropriate testing procedures are followed. Any perception by the public of drinking water contamination could significantly impact any offshore wind energy development. Early understanding and avoidance of issues regarding drinking water contamination could eliminate misunderstandings and potential major public backlash. This knowledge can be used to inform any public concerns and environmental impact assessments.

Recommended research activities include:

- Identifying buried contaminant areas offshore and nearshore where Great Lakes wind energy projects could be planned. New technologies may need to be developed to make this wind deployment possible (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Identifying safe methods of cable laying that reduce soil disturbance and resuspension; developing models to predict sediment transport (level of effort: $1–$2 million, timeline: 1–3 years)
- Identifying risk of resuspension of harmful contaminants. Metals, including mercury, polychlorinated biphenyls, and other persistent organic compounds are main concerns. The Huron-Erie corridor is one area that should be considered for examining, given the consequences of sediment resuspension (i.e., contaminants, seeding algal blooms,

nutrient eutrophication, and so on) (level of effort: $500,000−$1 million, timeline: 1−3 years)

- Assessing the risk that illegal dumping from public and private sectors near Great Lakes wind energy projects could have on drinking water (level of effort: $200,000−$500,000, timeline: 6 months−1 year)
- Assessing USACE dredging activities for effective water quality hazard mitigation (level of effort: $200,000−$500,000, timeline: 6 months−1 year).

8.2.3 Mitigate Impacts to Recreational and Commercial Fisheries

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	No	Yes	Medium

Description. The Great Lakes support commercial, recreational, and tribal fisheries in U.S. and Canadian waters that are collectively valued at more than $7 billion annually and support more than 75,000 jobs (GLFC 2014). Recreational fishing accounts for the vast majority of the fisheries value and includes salmon, walleye, trout, and muskellunge (e.g., Hohman and Hayes 2021). The commercial fishery encompasses species such as the lake whitefish, walleye, yellow perch, and ciscoes. Agencies stock fish in the Great Lakes each year to support the millions of anglers and to rehabilitate stressed fisheries. Each of the Great Lakes supports commercial fishing, with fishing pressure varying spatially based on the habitats that each species prefers (GLWC 2013). Lake Erie is the most productive of the Great Lakes and almost always produces more fish than any of the others (Reutter 2019). Anglers target species in a range of habitats that extend from the shoreline to the Canadian border. Most commercial fishing in the Great Lakes is done with gill, trap, or fyke nets, although trawls are used in certain places (e.g., Michigan Sea Grant 2022a; NYSERDA 2022a).

Some consideration has already been given to the potential impacts of Great Lakes wind energy development on fisheries in the region (GLWC 2013; LimnoTech 2017; NYSERDA 2022a). A workshop held by the Great Lakes Wind Collaborative identified the potential for wind turbine structures to act as aggregating devices in attracting a variety of fish species, sometimes known as “artificial reef” effects; anglers and fishers may target these structures as desired fishing locations (GLWC 2013). Alternatively, in some situations the area surrounding offshore wind energy foundations, buried cables, and midwater cables (in the case of floating turbines) may require restrictions on fishing or fishing methods or cause fishing vessels to avoid the area due to safety and gear damage concerns.

Overall, the GLWC workshop report recommends that developers should work with stakeholders to develop consensus on the use of offshore wind plants to protect the interests of both parties. A collaborative approach has been beneficial in U.S. Atlantic waters (e.g., NYSERDA 2022c). An understanding is needed of relevant historical fishing practices in the Great Lakes region, including the associated gear types and fishing requirements in potential areas for offshore wind energy development. Solutions can then be developed to ensure coexistence between the fishing and wind energy industries by avoiding interactions or developing mitigations and impact minimization measures.

Consequences and impact. Pushback from both recreational and commercial anglers against Great Lakes wind energy could delay projects and create negative public perceptions. Improved coexistence and communication with commercial and recreational fishers could lower project development costs and shorten timelines for development.

Recommended research activities include:

- Understanding fishing methods and requirements across gear types in potential wind energy development areas (level of effort: $500,000−$1 million, timeline: 1−3 years)
- Analyzing potential socioeconomic impacts on fisheries from Great Lakes wind energy development (level of effort: $1−$2 million, timeline: 3−5 years)
- Collating data and co-designing Great Lakes wind energy projects with fishers as an integral part of the planning process (level of effort: $1−$2 million, timeline: 1−3 years)
- Developing guidance for mitigating impacts to fisheries from Great Lakes wind energy development (level of effort: $1−$2 million, timeline: 3−5 years)
- Developing training for fishers to safely operate in and around wind farms (level of effort: $500,000−$1 million, timeline: 1−3 years).

9 Regulatory and Policy

9.1 Current Situation

A combination of state and federal policies will help determine the viability of Great Lakes wind as a contributor to the regional energy mix. From the federal perspective, the administration has a goal of reaching 30 GW of offshore wind energy by 2030, and 110 GW or more by 2050. On August 7, 2022, the Senate passed the Inflation Reduction Act of 2022 (IRA), which contains multiple provisions related to offshore wind energy (Congressional Research Service 2022). For example, the IRA contains a provision related to interregional and offshore wind electricity transmission planning, modeling, and analysis and would appropriate $100 million for convening stakeholders and conducting analysis related to interregional transmission development and offshore wind energy transmission development.

There are also other provisions related to transmission that could have implications for Great Lakes wind energy development. The primary federal tax provision supporting offshore wind is the investment tax credit, which provides a 30% tax credit for offshore wind energy projects that begin construction before January 1, 2026. Additionally, Section 13702 of the IRA provides a new clean electricity investment tax credit for the domestic production of wind energy components and related goods, such as specialized offshore wind energy installation vessels. The implications of the IRA and other federal policies need to be fully understood as part of research into the viability of future Great Lakes wind energy projects.

Current state policies for renewable energy and carbon reduction will play an important role in determining Great Lakes wind energy development, and a thorough analysis of policies is needed for each relevant state. A summary of clean energy goals for each state is presented here. Illinois, Michigan, New York, and Wisconsin have 100% clean energy goals by 2040 or 2050 (depending on the state) that have been established in existing policies (Clean Energy States Alliance undated; Table 5). Policy proposals in other Great Lakes states also indicate trends toward furthering clean energy goals. For Minnesota, Governor Tim Walz announced a path to clean energy in 2019 that is a set of policy proposals to lead the state to 100% clean energy in its electricity sector by 2050 (Minnesota 2019). In Ohio, the Energy Jobs and Justice Act (HB429) was introduced in 2021 and supports policies that are pushing the state to 100% clean energy by 2050 (The Ohio Legislature 2022). The *Pennsylvania Climate Action Plan* outlines a pathway to reaching the states greenhouse gas reduction goals: 26% by 2025 and 80% by 2050 from 2005 levels, as called for by Governor Tom Wolf in 2019 (Pennsylvania 2021).

There are various state and federal policies that would apply to the permitting path for wind energy development in each Great Lakes state, with some differences in implementation depending on unique considerations. All eight states have active Coastal Zone Management Act programs that work on state-specific coastal issues and would be involved in federal consistency reviews for any proposed wind energy projects (NOAA Office for Coastal Management 2022). Some or all states may follow a joint permitting process with USACE, which has responsibilities under the federal Rivers and Harbors Act, Clean Water Act, and National Historic Preservation Act (Michigan Great Lakes Wind Council 2010). Among other considerations, USACE would be responsible for issuing the Clean Water Act permit, such as for any dredged and fill materials associated with wind energy development, which would depend on state water quality certification and coastal management program consistency review. All potential Great Lakes wind energy projects will need to follow state environmental review and federal processes, such as those associated with NEPA review, as well as other relevant environmental laws (e.g., ESA, MBTA, and so on). These processes are likely to trigger review by the FWS, State and Tribal Historic Preservation Offices, U.S. Coast Guard, Department of Defense, and Federal Aviation Administration.

A state-by-state understanding of the permitting path needs to be developed to grasp the unique processes that would apply to Great Lakes wind energy development in each state's waters. As mentioned earlier, federal activities affecting a state's waters will trigger a Coastal Zone Management Act consistency review in the affected state. The Submerged Lands Act grants the Great Lakes states the authority to manage, administer, lease, develop, and use the lands beneath navigable waters within each state's boundaries (GLWC 2011a). It is worth noting that any state that has a federally approved coastal management program and has coastal resources that may be foreseeably affected by a project, even in another states' waters, could potentially request consistency review with their applicable enforceable policies.

For all of the Great Lakes states, the lakeward boundary of state jurisdiction extends to the international boundary between the United States and Canada, except in Lake Michigan where the boundaries have been determined by the states bordering that lake. Great Lakes wind energy structures located on state submerged lands, which would be leased to a developer, will require an easement of lands underwater from the appropriate state agency. For example, the New York State Office of General Services would handle such easements in its state waters (NYSERDA 2022a), and the Ohio Department of Natural Resources processes submerged land lease applications for its waters. The NYSERDA (2022a) study identified 15 major federal and state regulatory policies associated with permitting Great Lakes wind energy in New York waters. Depending on the state, other permitting processes may need to be considered including state dredge and fill permits, coastal erosion hazard areas permits, and incidental take permits for state-listed species.

Socioeconomic benefits are expected from increased state control of the wind energy leasing process in the Great Lakes, in comparison to other U.S. coastal areas where offshore wind energy leasing is taking place with greater federal control. With Great Lakes states in charge of the leasing and site control, revenues and economic benefits would flow to those states. At the same time, project certainty could increase, thereby potentially reducing costs during the development process. For example, the Michigan Great Lakes Wind Council (2010) identified avenues for recommended compensation to the public, including through rent, royalties, and establishing a Great Lakes wind trust fund. While it is likely that states will benefit from greater control of Great Lakes wind energy leasing processes and that there will be socioeconomic opportunities, there is still a lack of detail on the types of benefits and how they would be achieved. It is unknown how benefits could vary by state, how energy could be sold to adjacent states, and how much will be charged for royalties. These aspects require further research so that the socioeconomic opportunities and implications are better understood.

Table 5. State Clean Energy Goals in the Great Lakes Region

State	Goal	Comments
Illinois	100% clean energy by 2050	Legislation (SB2408) in 2021 established a goal of 100% clean energy by 2050, with interim targets of 40% by 2030 and 50% by 2040.
Indiana	10% clean energy by 2025	Indiana's clean energy portfolio standard sets a voluntary goal of 10% clean energy by 2025. While there is no state emissions standard, Indiana's utilities have established independent green house gas emissions reductions goals.
Michigan	Economywide carbon neutrality by 2050	Governor Gretchen Whitmer's order in 2020 (Executive Directive 2020-10) set a goal "to achieve economy-wide carbon neutrality no later than 2050." The Michigan Healthy Climate Plan was released in 2022.
Minnesota	Proposal for 100% clean energy by 2050	In 2019, Governor Tim Walz announced the One Minnesota Path to Clean Energy, a set of policy proposals for 100% clean energy in the state's electricity sector by 2050.
New York	100% carbon-free electricity by 2040	Legislation (S6599) in 2019 requires zero-emissions electricity by 2040 and sets a goal of cutting all state greenhouse gas emissions 85% by 2050; a climate action council will develop a plan.
Ohio	Proposal for 100% clean energy by 2050	In 2021, the Energy Jobs and Justice Act (HB429) was introduced, which would support policies pushing the state to 100% clean energy by 2050.
Pennsylvania	80% by 2050 from 2005 levels	Pennsylvania Climate Action Plan 2021 outlines a pathway to reaching Pennsylvania's greenhouse gas reduction goals: 26% by 2025 and 80% by 2050 (from 2005 levels).
Wisconsin	100% carbon-free electricity by 2050	Governor Tony Evers' Executive Order (EO38) in 2019 directed a new Office of Sustainability and Clean Energy to "achieve a goal" of all carbon-free power by 2050.

9.2 Key Challenges

9.2.1 Implement State-by-State Leasing and Permitting Studies

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Low

Description. Understanding of the offshore leasing process in each state is needed, given that the laws vary across states. Thus far, Ohio is the only state that has issued a lease for an offshore wind energy project. In addition, a thorough review is needed of the major federal, state, and utility permitting and regulatory authorizations that would likely be required for Great Lakes wind energy projects in a state's territorial waters. Across the Great Lakes, critical information is needed on the key regulatory and permitting processes, agencies involved, lessons learned from similar projects, and recommendations to ensure an efficient permitting process that would allow for maximum input and consideration from the public and other key stakeholders. Regulatory analyses can draw upon LEEDCo's permitting experience, expert interpretation of current state and federal policy, experience with comparable wind energy projects, and relevant agency guidance. For example, the recent NYSERDA (2022a) study identified and assessed 15 major federal and state permitting or regulatory requirements for New-York-based Great Lakes wind energy, as well as included recommendations for developing an efficient permitting process. The regulatory processes that would apply to Great Lakes wind energy are new to the various states bordering the lakes, which can result in ambiguity in how these processes would be utilized for wind energy in this region. It is essential that this analysis identify, in advance of development, any legal obstacles that may have been inadvertently passed into law before Great Lakes wind energy was under consideration.

A variety of federal and state policies will factor into the Great Lakes wind energy permitting process, with differences across states. Major federal policies that will impact wind deployment include the IRA, Jones Act, Federal Aviation Administration height restrictions, and NEPA, as well as the administration's offshore wind and clean energy targets for 2030 and 2050, respectively. State policies will be impacted by their clean energy goals, with several targeting 100% clean energy by 2040 and 2050 (Table 5; Clean Energy States Alliance undated).

With further analysis, the goals may help to facilitate the responsible deployment of Great Lakes wind energy in state waters, depending on what renewable energy mix makes sense in each state. For example, NYSERDA is actively analyzing Great Lakes wind energy development as part of its Climate Act (NYSERDA 2022a). In addition, Illinois has recently introduced a bill (HB4543; Illinois General Assembly 2022), which lays the groundwork for a proposed wind plant in Lake Michigan and sets up a fund that would help the state to compete for federal money, including for port infrastructure projects, with implications for Great Lakes wind energy development activities.

Consequences and impact. Given the unique regulatory processes involved with Great Lakes wind energy, there is likely to be some ambiguity in how these processes would be applied in each state, with potentially negative impacts on the ability to permit projects in a timely fashion. As a result, DOE has the opportunity to fund research that will provide greater regulatory clarity for potential projects in each state and to develop recommendations for streamlining permitting processes, with implications for project timelines and costs. Identifying potential obstacles to development in advance can potentially avoid years of regulatory delays.

Recommended research activities include:

- Assess leasing process in each state based on laws affecting Great Lakes wind energy development (level of effort: \$200,000−\$500,000, timeline: 6 months–1 year)
- Developing state and federal permitting road maps to understand steps in regulatory process (level of effort: \$500,000−\$1 million, timeline: 6 months–1 year)
- Identifying key regulatory issues and risks, including state and federal agency permitting considerations (level of effort: \$200,000−\$500,000, timeline: 6 months–1 year)
- Developing recommendations for efficient permitting processes (level of effort: \$200,000−\$500,000, timeline: 6 months–1 year)

- Assessing state benefits (e.g., revenue sources) from state control of leasing, permitting, and approval (level of effort: $500,000−$1 million, timeline: 6 months–1 year)
- Considering implications of state labor laws (level of effort: $200,000−$500,000, timeline: 6 months–1 year)
- Identifying and facilitating significant public/stakeholder input opportunities (level of effort: $500,000−$1 million, timeline: 1−3 years).

9.2.2 Assess Environmental and International Regulations

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	No	Yes	Medium

Description. A suite of environmental and international laws will apply to Great Lakes wind energy development and would need to be understood and navigated for project development. On the environmental side, primary relevant laws include NEPA, ESA, MBTA, and the Clean Water Act. Multiple federal and state agencies will be involved in these permitting and review processes, including USACE, FWS, EPA, NOAA, and various state agencies. Lessons have been learned from the LEEDCo IceBreaker's permitting process that could help inform and develop efficiencies involved with applying these laws to Great Lakes wind energy projects off each state.

In addition, NYSERDA (2022a) provided a series of recommendations and key steps for efficient permitting that could be further built on, including, for example: early engagement with regulators, relevant agencies, and key stakeholders; openly sharing information, regularly communicating Great Lakes wind energy project goals and objectives; and early establishment of the project's environmental goals. The NYSERDA report also identified policy uncertainty and compliance with the MBTA as a potential risk to wind energy projects, based on the lack of regulations, changing United States Department of Justice opinions, and potential to address prosecution differently across presidential administrations. Overall, addressing compliance and major risks at the outset of proposed projects and through early planning, including with public engagement, can allow the project itself to be optimized relative to permitting risks.

On the international side, an understanding is required of Canadian laws and regulations, including those related to Jones-Act considerations, as well as transboundary effects and how impacts are assessed through Canadian legislation. Canada is an active member of the Great Lakes Commission and shares in its commitment to balance the use, development, and conservation of the water resources of the Great Lakes, which would include considerations for wind energy development in the region. Canada has some experience with proposed Great Lakes wind energy projects (e.g., Trillium Wind Power Corporation) and can bring those lessons learned and potential opportunities, such as for joint infrastructure use, to bear on project development in U.S. waters.

Consequences and impact. The federal processes for Great Lakes wind energy are largely driven by or tied to the NEPA review process, which is likely to be triggered by obtaining a permit for dredged and fill materials from USACE and involves consultations and review by the FWS, State and Tribal Historic Preservation Offices, U.S. Coast Guard, and Federal Aviation

Administration. Given the number of agencies involved, as well as international considerations, there is a need to minimize risk related to the potential hurdles or difficulties that Great Lakes wind energy projects could face that could impede project activities. DOE has the opportunity to fund research that increases the efficiency of the environmental and international regulatory processes, the likelihood of successful permitting, and synergies among the processes.

Recommended research activities include:

- Contributing to information guidelines for environmental reviews of Great Lakes wind energy projects to help provide clarity for developers (level of effort: $500,000−$1 million, timeline: 1−3 years)
- Understanding policy uncertainty and compliance with MBTA, including opportunities for Canadian collaboration (level of effort: $200,000−$500,000, timeline: 6 months–1 year)
- Optimizing mitigation plans across multiple permitting agencies (level of effort: $500,000−$1 million, timeline: 1−3 years)
- Understanding implications of Canadian laws and treaties (level of effort: $200,000−$500,000, timeline: 6 months–1 year)
- Understanding implications of the Jones Act and use of Canadian ports and vessels (level of effort: $200,000−$500,000, timeline: 6 months–1 year).

9.2.3 Assess Infrastructure and Physical Regulations

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	No	Yes	Medium

Description. Legislative statutes, official regulations, and local policies may place restrictions on—or even preclude—some activities associated with offshore wind energy planning, installation, and maintenance. Also, it is possible that new restrictions may emerge over the next several years, because, with the exception of one major proposed project—LEEDCo Icebreaker—detailed consideration of actual Great Lakes wind energy projects has been minimal. Many government offices, tribes, commissions, advocacy groups, and other organizations have traditionally acted as stewards for the integrity, well-being, and economic prosperity of the Great Lakes and the surrounding communities and are likely to expand their scope into the wind power arena as Great Lakes wind energy becomes more prominent. A preliminary examination of materials from such groups—including the Great Lakes Commission (2022b); Michigan Department of Environment, Great Lakes, and Energy (2021); and the American Great Lakes Ports Association (2022)—indicates substantial attention to protecting the lakes and supporting the local economies but suggests little involvement to date with Great Lakes wind energy and its potential impacts.

In addition, the public utilities and public service commissions in each of the Great Lakes states have regulations that must be considered for constructing renewable energy projects and interconnecting renewable energy with the electric grid. However, there are uncertainties related to how existing regulatory authorities apply to Great Lakes wind energy development

(Wisconsin Public Service Commission 2009). As a result, a thorough examination is needed to identify those that may apply to Great Lakes wind energy additions on the region's electric power network.[12]

Note that some of these statutes and regulations protecting the Great Lakes will also have a few environmental characteristics, as identified in the previous section. The aim of the following research activities is to identify existing restrictions and requirements and anticipate those that have not yet been articulated. In addition, their impacts on Great Lakes wind energy development will be assessed and pathways and solutions for moving forward will be developed.

Consequences and impact. If these considerations are not addressed early, imposition of constraints after significant development resources have already been applied could lead to costly redesign or other modifications to program plans—or even cause project cancellation. Also, early identification of requirements, constraints, and associated issues are likely to affect locations and key features of Great Lakes wind power plants and related port facilities.

Recommended research activities include:

- Assessing impacts of electrical interconnection statutes and regulations (e.g., states, Federal Energy Regulatory Commission) on Great Lakes wind capacity additions (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Identifying statutes and regulations related to dredging and cable laying; assessing impacts on Great Lakes wind plants (level of effort: $200,000–$500,000 timeline: 1–3 years)
- Assessing potential for and impacts of radar interference from Great Lakes wind turbines; considering both military and civilian aviation and nautical navigation (level of effort: $500,000–$1 million, timeline: 1–3 years)
- Identifying and assessing regulations and restrictions related to buildout and management of ports; including overhead restrictions and power-line burial issues (level of effort: $1-$2 million, timeline: 1–3 years)
- Assessing regulations for vessel use, including Great Lakes wind energy installation, maintenance, and other access, and ice-breaking procedures (level of effort: $1–$2 million, timeline: 1–3 years).

[12] For example, the *Base Inventory of Regulatory Restrictions*. https://puco.ohio.gov/wps/wcm/connect/gov/7ab3a1dd-bff6-4ab4-a84d-d61802087bff/Final+Worksheet+PUCO+Public+12.27.2019.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE.Z18_K9I401S01H7F40QBNJU3SO1F56-7ab3a1dd-bff6-4ab4-a84d-d61802087bff-nfzVXsF.

10 Great Lakes Wind Energy Costs

Cost is one of the most important factors that influences decisions on whether and when to pursue the development of Great Lakes wind energy. The conditions in the Great Lakes are significantly different than ocean-based sites in the Atlantic, so regionally specific cost analysis is warranted and is presented herein. This section assesses the LCOE of Great Lakes wind energy under two scenarios for the reference year 2035 described in Section 2.0. The Current Scenario assumes minimal changes to Great Lakes infrastructure and draws from offshore wind technology that exists today. The Advanced Research Technology Scenario assumes that research and development of technology tailored to the Great Lakes environment and investment in regional infrastructure and supply chains enable, among many other things, the deployment of larger offshore wind turbines at lower cost. A comparison of LCOE between the two scenarios helps illustrate the potential impact of pursuing an aggressive research agenda targeting the high-priority challenge areas outlined in this report.

10.1 Overview of Cost Modeling Approach

LCOE represents the total cost per-unit of energy generated by a plant over its financial life. LCOE is calculated based on the definition from Short et al. (1995):

$$LCOE = \frac{(CapEx \times FCR) + OpEx}{(AEP \div P)} \quad (1)$$

where LCOE is the levelized cost of energy in terms of dollars per megawatt-hour ($/MWh), FCR is the fixed charge rate akin to a discount rate in terms of %/year, CapEx represents the total capital expenditures in terms of $/kilowatt (kW), OpEx represents the average annual operational expenditures per year expressed in $/kW-year, AEP is the average annual energy production over the life of the plant in terms of MWh/year, and P represents the total plant capacity in kilowatts.

LCOE can be useful for comparing costs of different generation sources, though care must be taken when doing so because differences in underlying assumptions such as financing terms or physical site parameters can substantially impact the resulting LCOE values. Note that LCOE does not account for different sources of project revenues or the value of a particular generation type to the grid.

This analysis incorporates a new offshore wind resource data set for the Great Lakes to assess future fixed-bottom and floating offshore wind energy costs based on potential development technology scenarios. A modeling process centered around NREL's Renewable Energy Potential Model (reV) is used to calculate site- and technology-specific Great Lakes wind energy costs by using the National Renewable Energy Laboratory Wind Analysis Library (NRWAL) to account for the impacts of spatial parameters such as water depths and distances to critical infrastructure (Figure 30). The Forecasting Offshore wind Reductions in Cost of Energy model (FORCE) is used to project costs in 2030 and 2035 based on expected cost reductions from technology learning, wind turbine upsizing, and technology innovation. A detailed description of each modeling tool is provided in the next section.

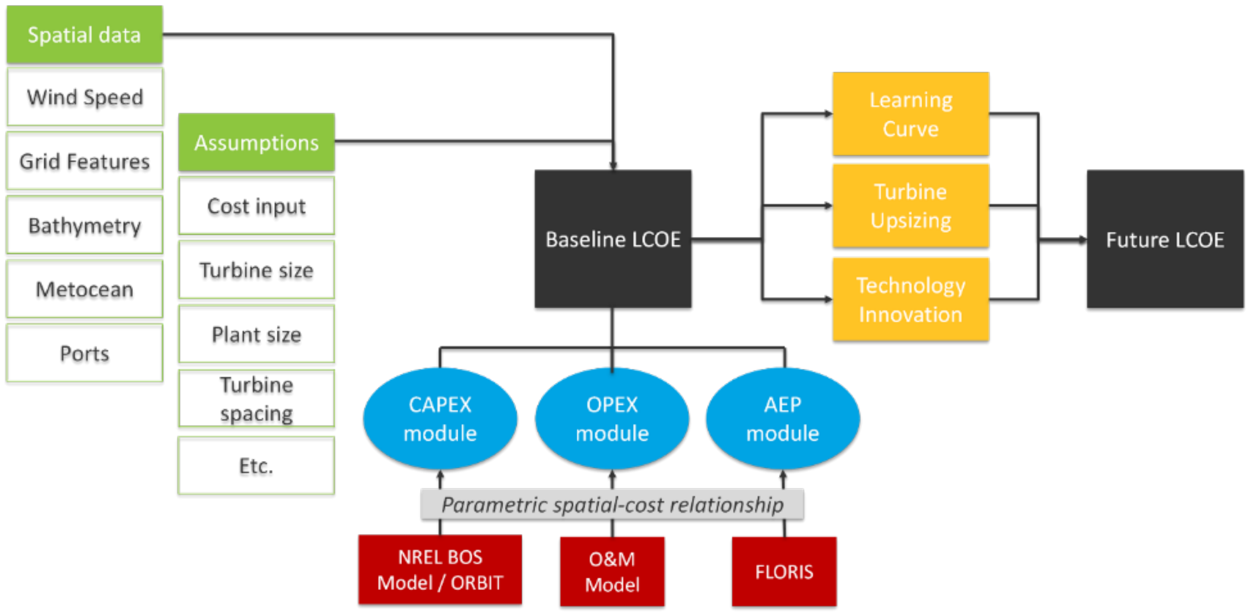

Figure 30. Summary of cost modeling process in NRWAL. ***Image based on Beiter et al. (2016, 2020)***

BOS = balance of system; FLORIS = FLOw Redirection and Induction in Steady State

The methodology outlined in the following sections is consistent with NREL's recent offshore wind energy cost assessments in New York State, Puerto Rico, Hawaii, Oregon, and California (NYSERDA 2022a; Duffy et al. 2022; Shields et al. 2022; Musial et al. 2021; Beiter et al. 2020). Note that this assessment presents unsubsidized LCOE values without policy incentives. Costs associated with bulk power system upgrades, which may be required to interconnect large generation projects, are also not included.

10.2 Cost Model Description

An overview of each modeling tool used to calculate Great Lakes wind energy costs and performance is provided here.

reV

The reV[13] model calculates renewable energy potential capacity, as well as site-specific power generation profiles and costs, by incorporating data on spatial drivers such as information about the resource, critical infrastructure, and land- or water-use characteristics (Maclaurin et al. 2021). To calculate offshore wind energy costs, reV relies on the NRWAL model, which is described next.

NRWAL

NRWAL[14] is a library of offshore-wind-energy-technology-specific spatial cost relationships derived from a combination of market data, bottom-up cost modeling, and industry feedback

[13] Access the model by visiting: https://www.nrel.gov/gis/renewable-energy-potential.html.
[14] Access the model on GitHub: https://github.com/NREL/NRWAL.

(Nunemaker et al. 2021; NREL 2022b). The model is an open-sourced version of NREL's Offshore Regional Cost Analyzer model (Beiter et al. 2016), which is easy to update based on the latest market trends and local conditions. reV uses NRWAL in regional- or national-scale offshore wind energy cost assessments to calculate site-specific CapEx and OpEx values that account for cost impacts of spatial variables, such as water depth, distances to ports, and points of interconnection in the transmission system.

ORBIT

ORBIT[15] is used to confirm and update the spatial cost relationships in NRWAL by modeling wind turbine installation strategies for different technologies (Nunemaker et al. 2020).

FORCE

FORCE[16] model is used to calculate cost reductions over time resulting from supply chain maturity and technology innovations (Shields et al. 2022).

10.3 Technology Modeling Assumptions

10.3.1 Technology Scenarios

Two scenarios are defined here to assess the possible impacts of research addressing the challenge areas presented in this report. The first assumes minimal changes to current technology and infrastructure around the Great Lakes, whereas the second assumes that focused research and development enable the installation of larger wind turbines and associated cost benefits, and region-specific design optimization. The timeframe for both scenarios is 2035.

Current Scenario

The Current Scenario assumes that wind energy technology deployed in the Great Lakes uses designs from land- and ocean-based wind power plants without significant customization for the Great Lakes environment. Conventional offshore substructures are adapted with add-ons, such as ice cones or suction buckets, without substantially altering the design. Maintenance operations are limited by ice conditions in winter months, lowering availability, and mitigation of blade icing adds to wind turbine supply costs. Port infrastructure undergoes the minimum upgrades to enable substructure and wind turbine assembly and installation vessels are limited to small jack-up vessels that can transit the St. Lawrence Seaway or ad hoc solutions such as crawler cranes supported by barges. Because of infrastructure limitations, the Current Scenario does not allow for large turbines of 15 MW or more that are expected to be used at ocean-based offshore wind sites in 2035. Instead, wind turbines in this scenario leverage land-based wind supply chains, wherein ratings of 5−7 MW are expected to be typical in 2035. The wind turbine model used in this analysis is taken from NREL's 2022 Annual Technology Baseline (ATB), land-based wind 2030 "Moderate" case (NREL 2022a). The wind turbine has a rated capacity of 5.5 MW, rotor diameter of 175 m, and hub height of 120 m.

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[15] Access the model on GitHub: https://github.com/WISDEM/ORBIT.
[16] Access the model on GitHub: https://github.com/NREL/FORCE.

Advanced Research Technology Scenario

The Advanced Research Technology Scenario assumes that targeted research and investment in Great Lakes' infrastructure enable optimization of wind energy technology for the region. Specifically, support structure designs are tailored to the region's ice climate, lakebed conditions, and vessel constraints, enabling the installation of larger wind turbines. These designs are assumed to leverage regional manufacturing capabilities to develop a supply chain capable of delivering components at the same cost level as East Coast offshore wind components. Upgrades to port infrastructure are targeted at offshore-scale turbines and regional substructure designs, which are likely to rely heavily on port-based lifting capabilities and float-out strategies due to the constraints on vessel size. Innovative maintenance strategies reduce winter downtime and achieve availability levels equal to ocean-based offshore wind power plants. The wind turbine model used in this scenario is an adaptation of the International Energy Agency Wind 15-MW reference wind turbine (Gaertner et al. 2020), scaled up to 17 MW with a larger rotor for increased power capture at low wind speeds.

Table 6. Key Assumptions for Cost Scenarios

Scenario	Current	Advanced Research Technology
Wind Turbine Size	5.5-MW Annual Technology Baseline turbine	17-MW scaled reference turbine
Vessels	Constrained by locks; improvised vessels	Solutions do not require large installation vessels (e.g., float-out foundations)
Ports	Land-based cranes	Custom, heavy-lift, high-capacity ports
Operations and Maintenance	Access constrained by level ice; availability degraded	Innovations to address access; availability recovered
System Design	Premium on ice mitigation; limited ice designs	Optimized ice designs

Power curves for the Current and Advanced Research Technology scenarios are presented in Figure 31, and key wind turbine parameters in Table 6. Note that both machines have lower specific power ratings than current offshore wind turbines, and the ATB 5.5-MW land-based turbine used for the Current Scenario has a specific power rating that is much lower than what is typically used in areas with mean wind speeds as high as those in the Great Lakes. This assumption may result in higher annual energy output calculations for the Current Scenario.

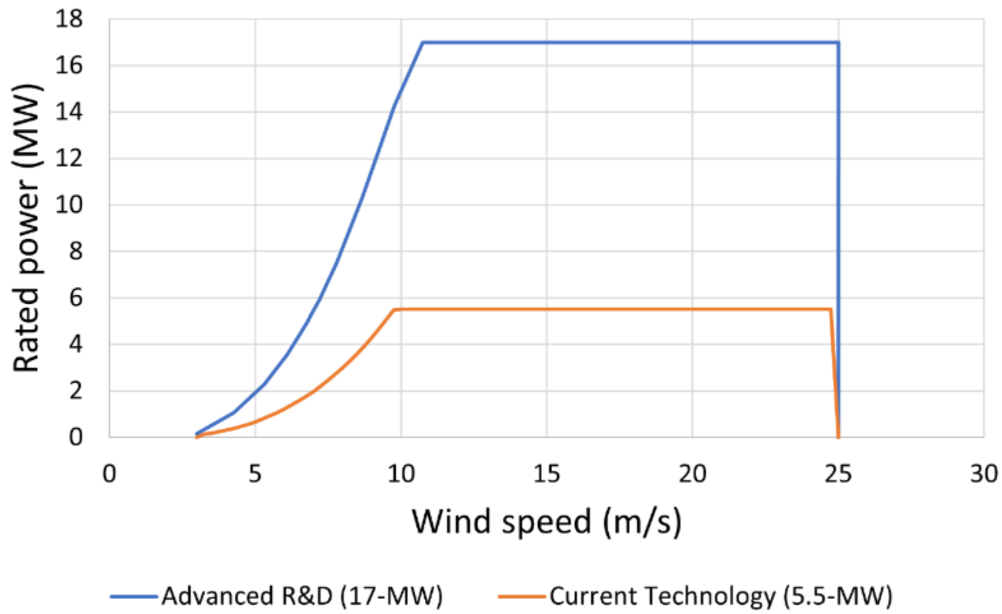

Figure 31. Power curves for the Advanced and Current scenarios

Table 7. Wind Turbine Parameters Used in the Current and Advanced Scenarios

Scenario	Current	Advanced Research Technology
Rated power (MW)	5.5	17
Rotor diameter (m)	175	278
Hub height (m)	120	168
Specific power (W/m^2)	229	280

10.3.2 Financing Assumptions

For this analysis, Great Lakes wind energy project financing assumptions are assumed to be in line with commercial-scale offshore wind projects. The real and nominal FCR values of 5.82% and 7.64% are used in calculating LCOE, and results are presented in nominal terms, meaning that effects of inflation between the commercial operation date year and end of the project life are ignored. These financing terms are calculated in line with recent updates in Duffy et al. (2022) and have been informed by literature and updated based on conversations with industry partners (Feldman, Bolinger, and Schwabe 2020; NREL 2022a; Guillet 2018). A summary of the parameters used to calculate FCR is presented in Table 8, and a more detailed description of each term can be found in Beiter et al. (2016). The standard depreciation schedule for wind energy projects, the 5-year Modified Accelerated Cost Recovery System, is chosen for the calculation. No policy incentives or subsidies are included in the cost analysis.

Table 8. Summary of Great Lakes Wind Energy Project Financing Parameters

Parameter	Value
Capital recovery period, years	25
Tax rate, %	26
Inflation (long-term average), %	2.5
Share of debt, %	67
Nominal debt rate, %	4.0
Nominal return on equity, %	10.0
Nominal after-tax weighted-average cost of capital, %	5.29
Real after-tax weighted-average cost of capital, %	2.72
Nominal after-tax capital recovery factor, %	7.3
Real after-tax capital recovery factor, %	5.6
Depreciation basis, %	100
Depreciation schedule	5-year Modified Accelerated Cost Recovery System
Present value of depreciation, %	87
Project finance factor, %	105
Nominal after-tax FCR, %	**7.64**
Real after-tax FCR, %	**5.82**

10.3.3 Cost Projection Methodology

We used the FORCE model to implement a learning-curve-based cost projection methodology developed by Beiter et al. (2020) and summarized in Duffy et al. (2022) to estimate future Great Lakes wind energy costs. Future costs are calculated by combining cost reductions resulting from supply chain learning, technological innovations, economies of scale, and investment with baseline cost estimates obtained with reV and NRWAL. We used an offshore wind learning rate to describe the percentage cost reduction for each doubling of installed capacity. Both the Current and Advanced Research Technology scenarios use the same learning rates, which are derived from global offshore wind deployment levels and are not regionally specific.

Learning rates are derived with the FORCE model based on a regression of offshore wind energy project CapEx data going back to 2014. Because limited floating offshore wind cost data are available in 2022, commercial-scale, fixed-bottom cost data are analyzed to obtain the experience factor for floating offshore wind. Parameters such as wind turbine rating, plant capacity, water depth, distance to shore, and installation country are controlled for in the FORCE regression because their cost impacts are already accounted for in NRWAL.

Once a learning rate is obtained, it is used to derive a learning curve that describes cost reductions over time. This process requires estimating global offshore wind energy deployment in specific future years. For this analysis, we assumed the same levels of deployment used in Duffy et al. (2022) (Table 9).

Table 9. Summary of Global Offshore Wind Energy Deployment Projections Used to Derive Learning Curves. ***Reproduced from Duffy et al. (2022)***

Year	Data Sources	Fixed Capacity	Floating Capacity
2020 Deployment	Musial et al. (2021)	32.9 GW	0.08 GW
2030 Deployment	Global Wind Energy Council (2016), 4C Offshore, Equinor, Wood Mackenzie, Strathclyde	229 GW	9.7 GW
2035 Deployment	ORE Catapult	277 GW	14.4 GW
CapEx Learning Rate	FORCE model	7.3%	7.3%

Figure 32 presents offshore wind CapEx learning curve cost reductions as a percentage of base year costs. Note that this methodology predicts more aggressive cost reductions (in % terms) for floating offshore wind because more "doublings" of the global floating offshore wind capacity are expected as the technology rapidly develops in the coming years. Present-day floating offshore wind costs are higher than fixed-bottom costs.

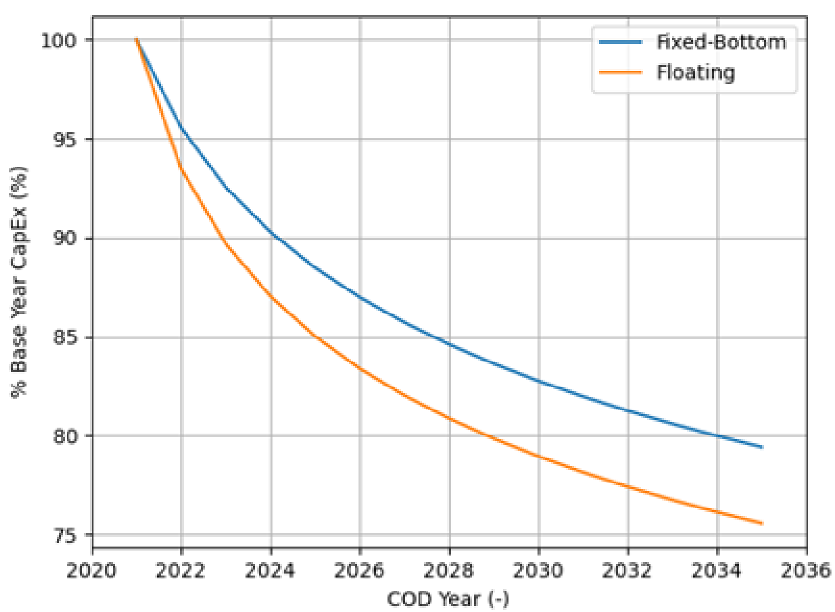

Figure 32. Projected CapEx learning cost reductions for fixed-bottom and floating offshore wind through 2035. ***Reproduced from Duffy et al. (2022)***

We derived cost reductions associated with OpEx and AEP from expert elicitation because public data on project O&M cost and annual energy production are unavailable to derive learning curves for OpEx and AEP. Based on Wiser et al. (2021), total OpEx reductions of 12% are assumed between 2019 and 2035 for fixed-bottom wind and 22% for floating wind. AEP improvements of 7% and 11%, respectively, are assumed over the same period. Future LCOE is calculated after cost reductions have been applied to each primary input. No differences in financing terms are assumed over time.

10.4 Cost Results

This section presents technical potential capacities for each of the Great Lakes, as well as the resulting 2035 CapEx, OpEx, net capacity factor (NCF), and LCOE estimates for both the Current and Advanced Research Technology scenarios. We used heat maps of cost parameters to show the spatial differences and tables summarize averages and ranges of these parameters. We used an LCOE difference map to highlight the potential impact of pursuing an aggressive research platform on LCOE. More investigation is needed to better understand how lower costs resulting from the Advanced Research Technology Scenario could impact the timeline and quantity of Great Lakes wind energy deployment.

10.4.1 Generation Potential in the Great Lakes

Figure 33 breaks down the wind energy generation potential by distance from shore and technology type (fixed bottom or floating). The area between 0 and 3 miles from shore is not counted. The area of the Great Lakes is large enough for multiple gigawatts of electricity to be generated from each lake. Actual levels of deployment will be informed by a variety of considerations, including the economic factors analyzed here. The total potential capacities in Figure 33 are presented for all areas in the model, but the cost results include only grid cells that can hold at least 900 MW of capacity.

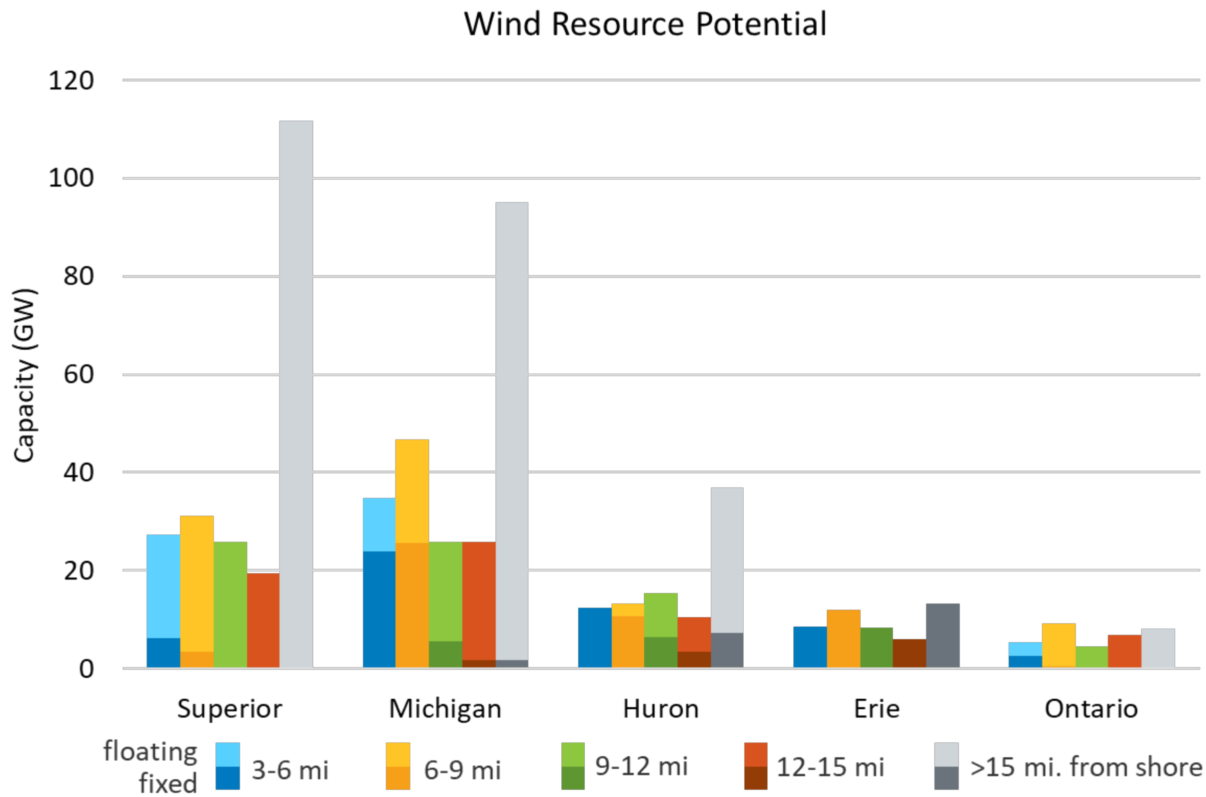

Figure 33. Great Lakes wind resource potential breakdown by distance to shore, by lake from west to east, and assuming an array density of 5 MW/km^2

As shown in Figure 33, Lake Michigan and Lake Superior have the largest total potential offshore wind capacities in the Great Lakes (approximately 230 GW and 220 GW, respectively). Much of this floating capacity exists in waters more than 15 miles (mi) from shore (grey bars). Lake Ontario has the least total potential capacity, at around 35 GW.

Figure 33 also indicates that most of the potential capacity in Lake Superior, Lake Michigan, and Lake Ontario is far from shore where water depths are more suitable for floating substructure technology (greater than 60 m deep). Shallower waters mean that offshore wind deployed in Lake Erie would likely use fixed-bottom substructure technologies. Most of the capacity close to shore in Lake Huron is in shallower water.

10.4.2 CapEx

Figure 34 and Figure 35 present heat maps of CapEx in 2035 for the Current Scenario (5.5-MW wind turbines) and Advanced Research Technology Scenario (17-MW wind turbines), respectively. Across all the Great Lakes, CapEx for the Current Scenario ranges from \$2,000/kW to \$3,600/kW, with a mean of \$2,993/kW. Under the Advanced Research Technology Scenario, this range falls to between \$1,900/kW and \$2,600/kW, with a mean of \$2,178/kW. In both scenarios, the lowest costs are found in Lake Erie and Lake Michigan, whereas the highest costs are found in Lake Superior. Locations in Lake Superior with the highest costs are in deeper waters far from the port of Duluth and points of interconnection.

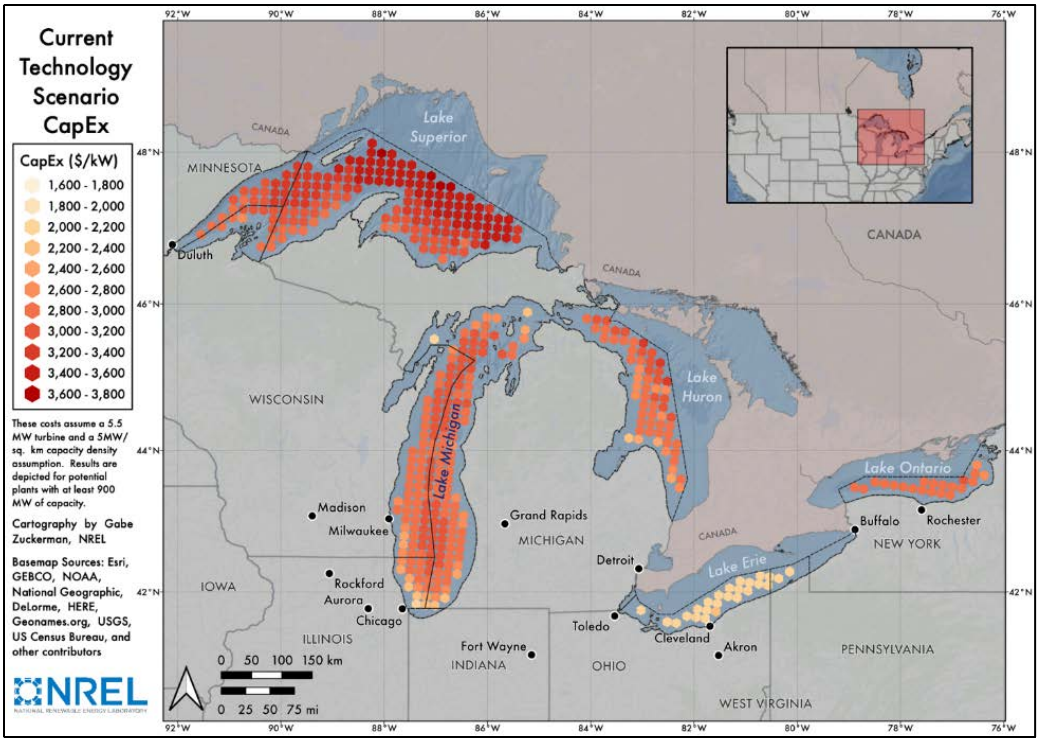

Figure 34. Modeled CapEx in 2035 for the Current Scenario. ***Map from NREL***

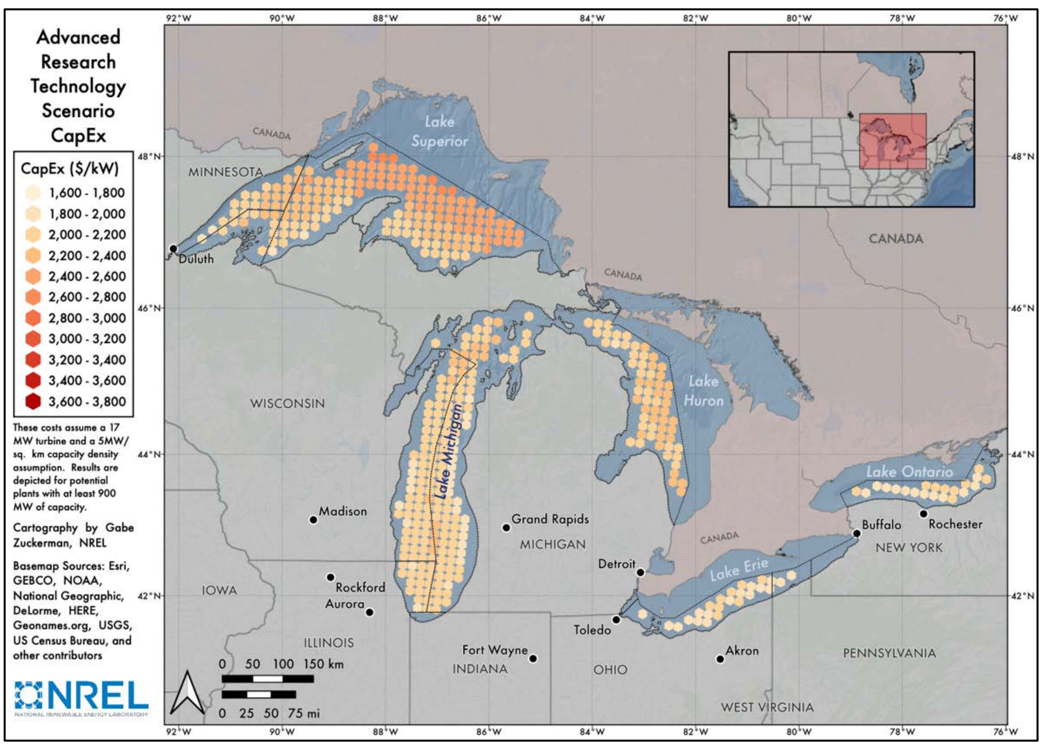

Figure 35. Modeled CapEx in 2035 for the Advanced Research Technology Scenario. ***Map from NREL***

Table 10 provides an itemized breakdown of CapEx for the Advanced Research Technology Scenario, averaged across the fixed-bottom sites in each lake. For fixed-bottom sites, water depth is a major driver of the CapEx differences between lakes, which is indicated by the variation in average substructure and foundation costs. Substructure installation costs represent another significant contributor to difference in average CapEx between lakes, which are driven by distance to the installation port and water depth. Wind turbine procurement, which is subdivided into the cost of the tower and the rotor nacelle assembly, has a constant value across all sites. In Lake Erie, which has the lowest average CapEx, this cost represents a larger share of the total.

Table 10. Summary of CapEx Line Items Expressed As a Percent of Total CapEx Based on Mean Values in Each Lake for Fixed-Bottom Technology in 2035 for the Advanced Research Technology Scenario

Line Item [Values in % of Total CapEx]		Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Turbine	Tower	4.3%	4.5%	4.3%	4.8%	4.4%
	Rotor Nacelle Assembly	26.4%	27.8%	26.5%	29.5%	27.1%
Balance of System	Substructure and Foundation	16.4%	16.3%	16.9%	13.9%	17.3%
	Port, Staging, Logistics, and Fixed Costs	1.2%	1.3%	1.2%	1.3%	1.2%
	Turbine Installation	2.2%	2.2%	2.3%	2.5%	2.0%
	Substructure Installation	5.6%	4.7%	5.6%	4.0%	4.4%
	Array Cabling	7.7%	8.1%	7.8%	8.3%	8.1%
	Export Cable	11.9%	10.9%	11.1%	11.5%	11.7%
	Development	3.0%	3.0%	3.0%	3.0%	3.1%
	Lease Price	4.1%	4.5%	4.2%	4.7%	4.3%
	Project Management	1.5%	1.5%	1.5%	1.5%	1.5%
Soft Costs	Insurance During Construction	2.0%	2.0%	2.0%	2.0%	2.0%
	Project Completion	1.0%	1.0%	1.0%	1.0%	1.0%
	Decommissioning	1.4%	1.2%	1.4%	1.1%	1.1%
	Procurement Contingency	4.4%	4.5%	4.4%	4.5%	4.5%
	Installation Contingency	2.7%	2.4%	2.7%	2.2%	2.2%
	Construction Financing	4.1%	4.1%	4.1%	4.1%	4.1%
Mean Total CapEx for Advanced Research Technology Scenario [$/kW]		**$2,323**	**$2,115**	**$2,215**	**$1,988**	**$2,140**

Table 11 provides an itemized breakdown of CapEx for the Advanced Research Technology Scenario, averaged across the floating sites in each lake. Note that there are no floating sites in Lake Erie. Distances to points of interconnection drive some of the variation in costs, notably in parts of Lake Superior where the required export cable lengths are longer than in other lakes.

Substructure and foundation costs, which are strongly influenced by water depth, also help explain variation between average floating offshore wind CapEx in each lake. The constant turbine procurement cost makes up the largest share of the total in Lake Ontario, where the average CapEx is lowest. The average CapEx for floating technology is slightly lower than for fixed-bottom wind turbines in each of the four lakes with deep water.

Table 11. Summary of CapEx Line Items Expressed As a Percent of Total CapEx Based on Mean Values in Each Lake for Floating Technology in 2035 for the Advanced Research Technology Scenario

Line Item [Values in % of Total CapEx]	Lake Superior	Lake Michigan	Lake Huron	Lake Erie	Lake Ontario
Tower	4.1%	4.4%	4.3%	N/A	4.6%
Rotor Nacelle Assembly	24.9%	26.9%	26.6%	N/A	28.3%
Turbine Supply					
Substructure	12.8%	13.5%	12.1%	N/A	14.3%
Foundation	5.0%	5.6%	6.6%	N/A	5.9%
Support Structure					
Port, Staging, Logistics, and Fixed Costs	1.4%	1.4%	1.4%	N/A	1.4%
Turbine Installation	1.7%	1.3%	1.7%	N/A	1.4%
Substructure Installation	0.7%	0.7%	1.5%	N/A	0.7%
Total Installation					
Array Cabling	8.8%	9.0%	8.7%	N/A	9.8%
Export Cable	18.7%	15.2%	14.7%	N/A	11.1%
Total Electric System					
Development	3.1%	3.1%	3.1%	N/A	3.1%
Lease Price	4.0%	4.3%	4.3%	N/A	4.5%
Project Management	1.6%	1.6%	1.6%	N/A	1.6%
Balance of System					
Insurance During Construction	2.1%	2.1%	2.1%	N/A	2.1%
Project Completion	1.0%	1.0%	1.0%	N/A	1.0%
Decommissioning	0.4%	0.4%	0.6%	N/A	0.5%
Procurement Contingency	4.9%	4.9%	4.8%	N/A	4.9%
Installation Contingency	0.8%	0.7%	1.1%	N/A	0.7%
Construction Financing	4.1%	4.1%	4.1%	N/A	4.1%
Total Soft CapEx					
Mean Total CapEx for the Advanced Research Technology Scenario [$/kW]	**$2,321**	**$2,087**	**$2,147**	N/A	**$1,992**

10.4.3 OpEx

OpEx encompasses all costs associated with operating a wind power plant, including labor, vessels, and materials used for maintaining the plant, onshore facilities, insurance, management, and support services. Estimated 2035 OpEx costs for the Current Scenario and Advanced Research Technology Scenario are presented in Figure 36 and Figure 37, respectively. Across all lakes in the Current Scenario, OpEx ranges from $85/kW-yr to $156/kW-yr, with a mean of $122. Under the Advanced Research Technology Scenario, OpEx ranges from $63/kW-yr to $96/kW-yr, with a mean of $79. One of the primary drivers of cost reduction between the two scenarios is wind turbine upsizing, because fewer 17-MW turbines are needed for the same plant capacity, which allows for fewer maintenance operations. Within each scenario, higher O&M costs were estimated for sites that are farther from the operations port and sites with higher average significant wave heights. As noted in Section 3, the availability of observational wave data is limited during the winter months. Improved wave height measurements could lead to adjustments in the estimated OpEx for some sites.

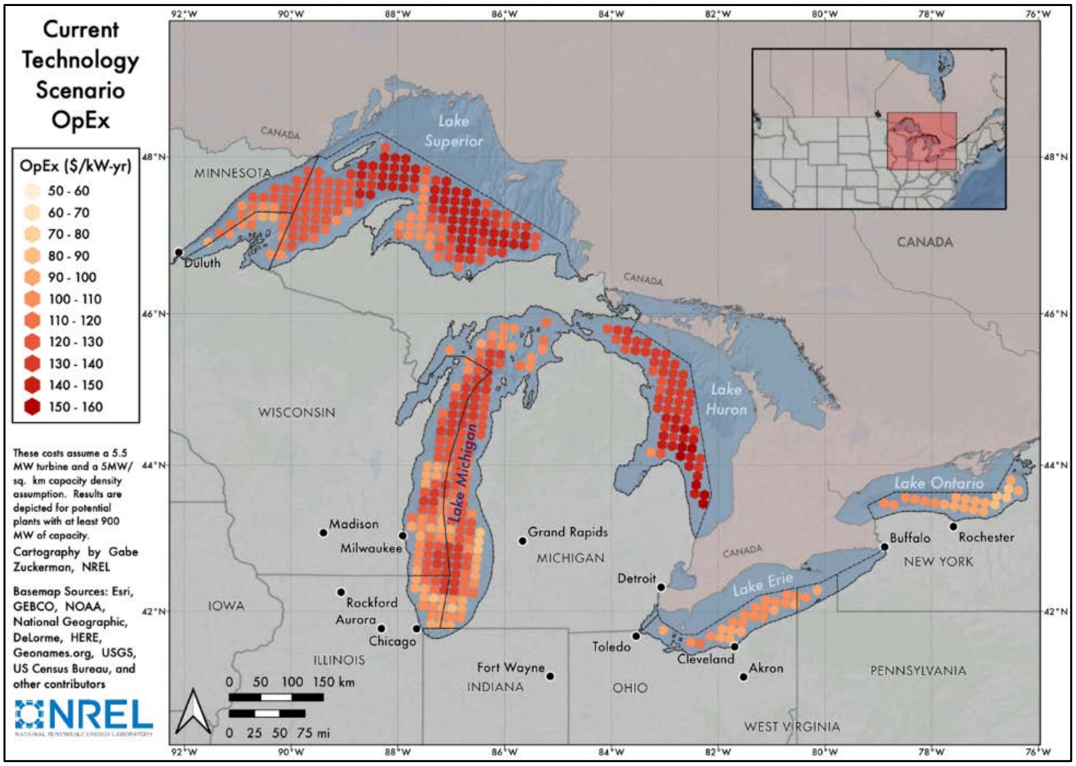

Figure 36. Modeled OpEx in 2035 for the Current Scenario. ***Map from NREL***

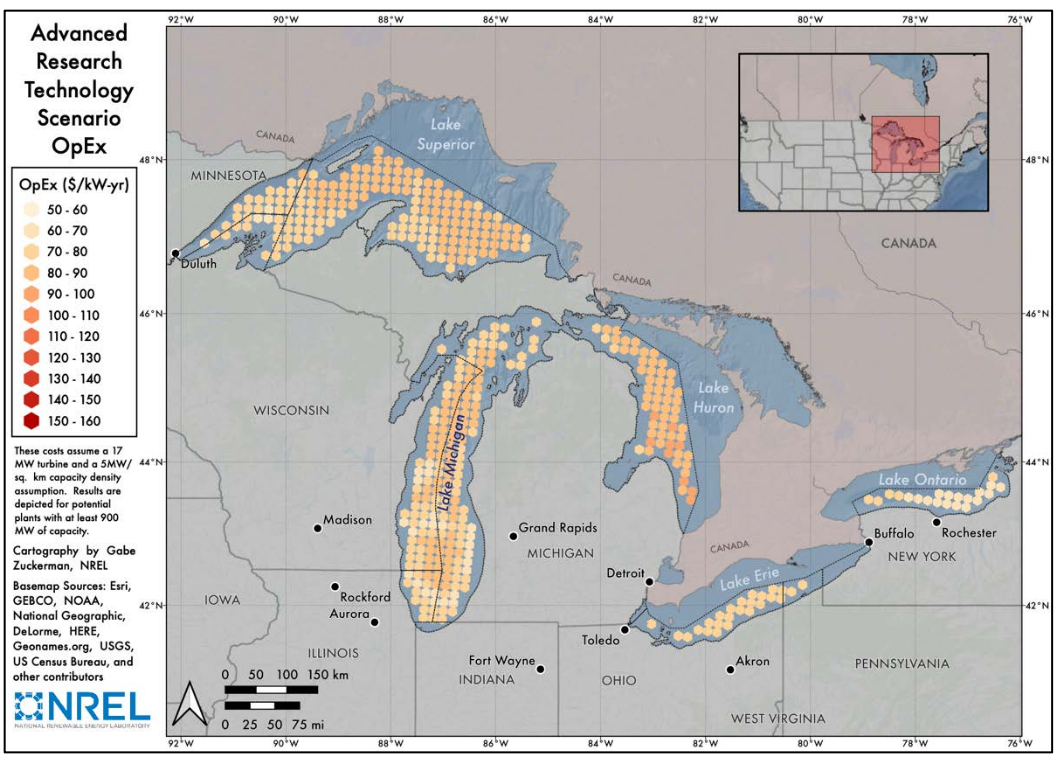

Figure 37. Modeled OpEx in 2035 for the Advanced Research Technology Scenario. ***Map from NREL***

Table 12 summarizes the average OpEx in each lake by substructure technology. Floating O&M costs are slightly higher than fixed-bottom O&M costs in Lake Superior and Lake Michigan. The opposite is true in Lake Huron and Lake Ontario. On average, the Advanced Research Technology Scenario brings O&M costs down by between 27% and 36% for fixed bottom and 29% and 38% for floating offshore wind relative to the Current Scenario.

Table 12. Summary of Mean OpEx by Lake for the Current and Advanced Research Technology Scenarios

Values Expressed As [$/kW-yr]	Lake Superior		Lake Michigan		Lake Huron		Lake Erie		Lake Ontario	
	Fixed	Float	Fixed	Float	Fixed	Float	Fixed	Float	Fixed	Float
2035 OpEx (Current)	111	129	103	118	141	136	102	N/A	98	96
2035 OpEx (Advanced Research Technology)	77	81	74	77	89	84	74	N/A	71	68

10.4.4 Annual Energy Production/Net Capacity Factors

We calculated net capacity factors for each location and scenario using the power curves in Figure 31 and wind speeds at hub height based on NREL's Great Lakes offshore wind resource data.[17] Heat maps depicting wind power plant performance in terms of NCF are presented in Figure 38 and Figure 39 for the Current and Advanced Research Technology Scenarios, respectively. NCF values range from 42% to 59% with a mean of 52.6% with current technology, and range from 41% to 57% with a mean of 51.1% with advanced technology. The lower specific power and rated wind speed of the 5.5-MW land-based wind turbine deployed in the Current Scenario led to a greater NCF than the 17-MW turbine assumed in the Advanced Research Technology Scenario. Future work is needed to better characterize the wind resource and identify the most appropriate specific power for Great Lakes wind turbines. Table 13 summarizes the average NCF in each lake by substructure technology.

The wind resource is the main driver of differences in NCF. Lake Michigan, Lake Superior, and Lake Huron have the highest NCF values because they have the highest wind speeds throughout the year. Figure 4 indicates that 21-year average wind speeds at a 140-m height reach 9.6 m/s in large portions of each of these lakes. Lake Ontario has the lowest mean wind speeds, but they still reach up to 9.2 m/s in portions of the lake. The highest wind speeds are typically found near the center of each lake, which leads to higher capacity factors for floating sites in some cases.

[17] Great Lakes offshore wind resource data can be accessed at https://doi.org/10.25984/1821404.

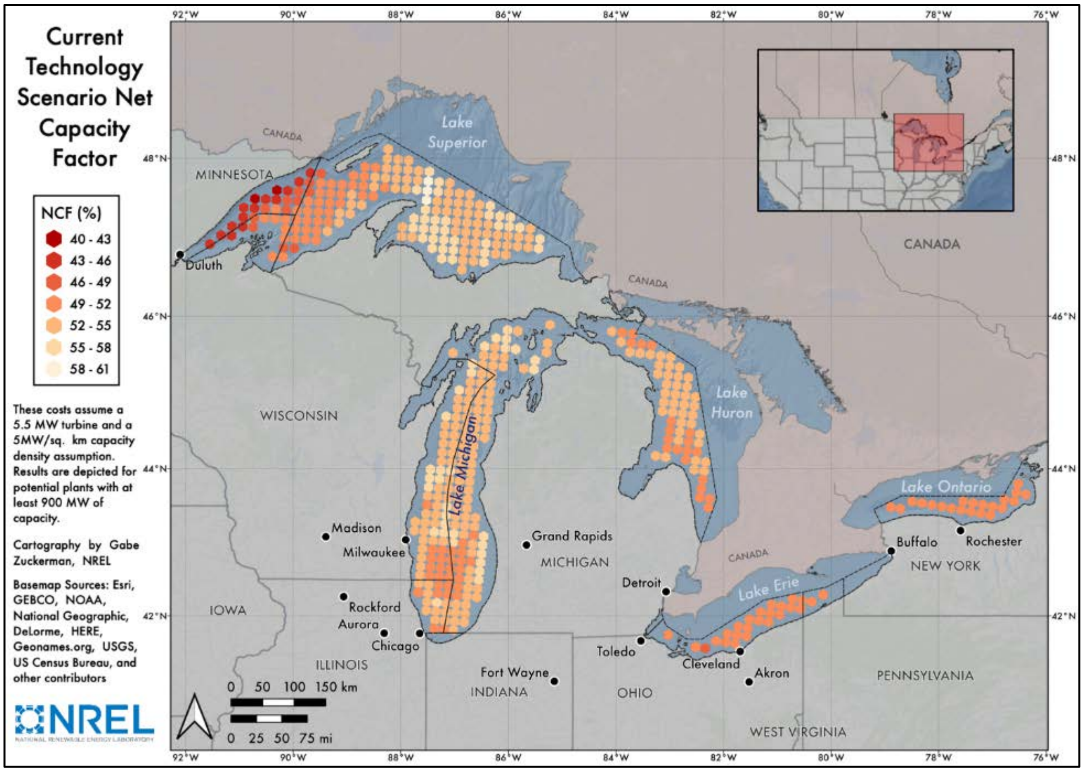

Figure 38. Modeled net capacity factors in 2035 for the Current Scenario. ***Map from NREL***

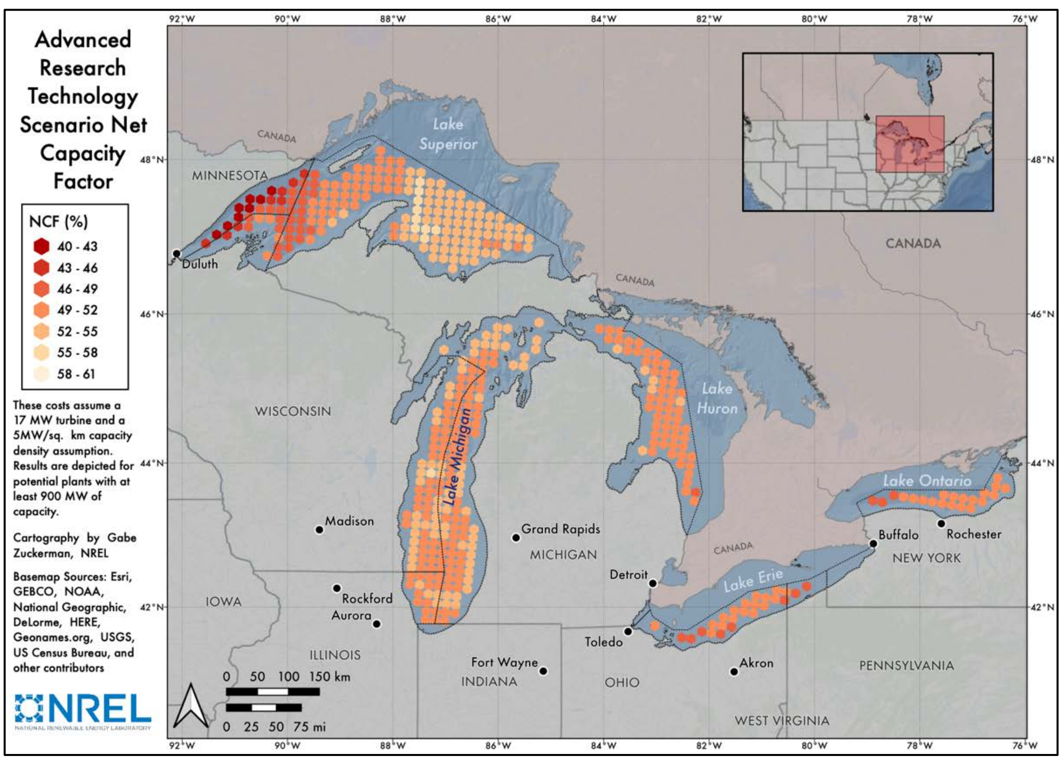

Figure 39. Modeled NCF in 2035 for the Advanced Research Technology Scenario. ***Map from NREL***

Table 13. Summary of Modeled NCF for the Current and Advanced Research Technology Scenarios

Values Expressed As [%]	Lake Superior		Lake Michigan		Lake Huron		Lake Erie		Lake Ontario	
	Fixed	Float	Fixed	Float	Fixed	Float	Fixed	Float	Fixed	Float
2035 NCF (Current)	48	52	53	53	52	53	51	N/A	51	51
2035 NCF (Advanced Research Technology)	47	51	52	52	51	51	49	N/A	50	50

10.4.5 LCOE

Site-specific LCOE values are calculated using the CapEx, OpEx, and NCF data presented earlier. The 2035 LCOE estimates for the Current Scenario range from $75/MWh to $129/MWh, as shown in Figure 40. The mean LCOE across all lakes in the Current Scenario is $103/MWh. Figure 41 shows that LCOE for the Advanced Research Technology Scenario ranges from $62/MWh to $89/MWh, with a mean of $74/MWh.

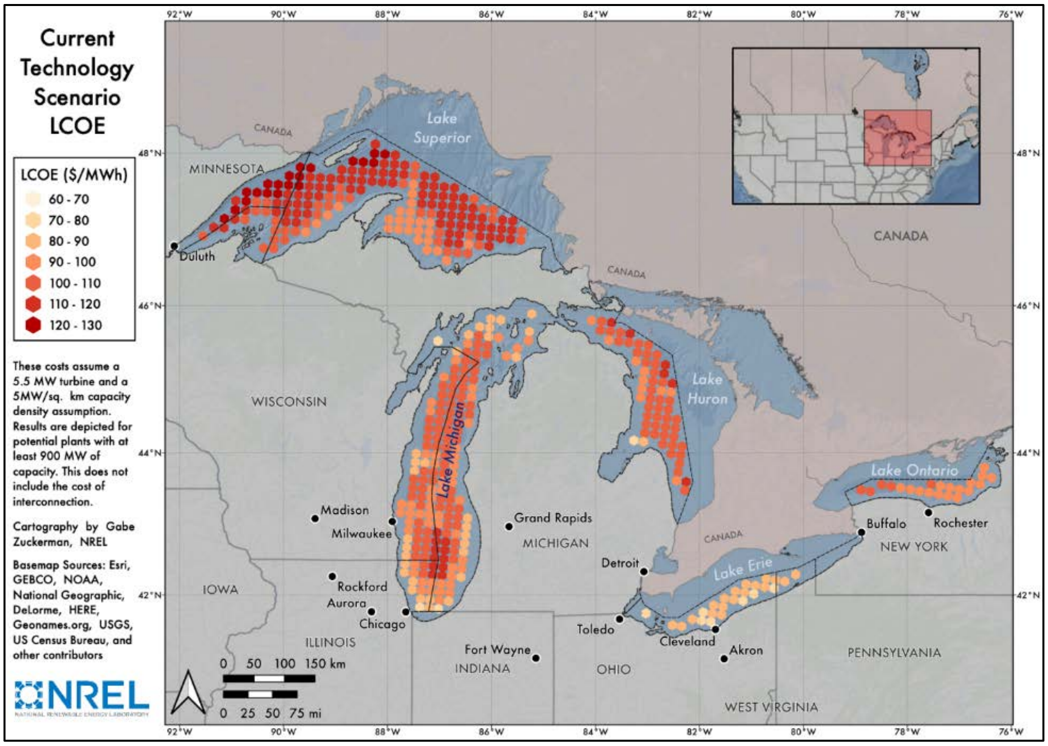

Figure 40. Modeled LCOE in 2035 for the Current Scenario. ***Map from NREL***

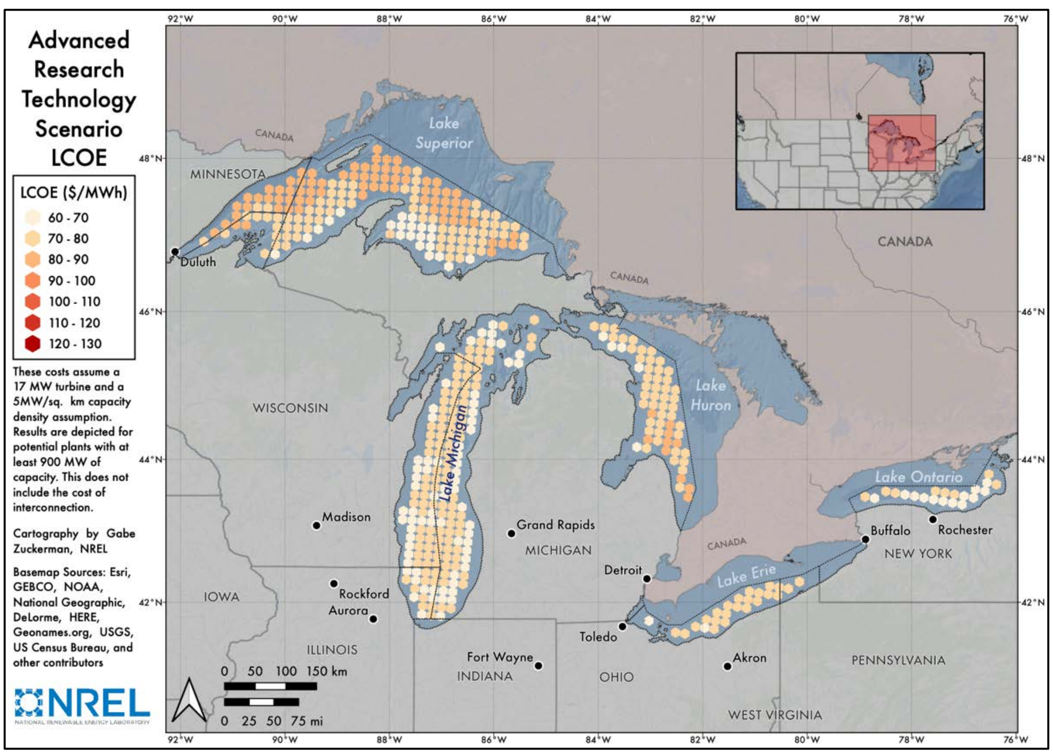

Figure 41. Modeled LCOE in 2035 for the Advanced Research Technology Scenario. ***Map from NREL***

Table 14 presents average 2035 LCOE by lake and substructure technology. Lake Erie has the lowest average LCOE in the Current Scenario, but the Advanced Research Technology Scenario indicates that costs in Lake Michigan could be lower than in Lake Erie as a result of higher capacity factors in Lake Michigan and CapEx reductions between the scenarios. Across substructure technologies and scenarios, Lake Superior has the highest average LCOE resulting from high CapEx and OpEx costs, as well as lower wind speeds on the western portion of the lake.

Table 14. Summary of Mean Modeled LCOE for the Current and Advanced Research Technology Scenarios

Values Expressed As [$/MWh]	Lake Superior		Lake Michigan		Lake Huron		Lake Erie		Lake Ontario	
	Fixed	Float	Fixed	Float	Fixed	Float	Fixed	Float	Fixed	Float
2035 LCOE (Current)	102	111	86	101	101	106	81	N/A	92	97
2035 LCOE (Advanced Research Technology)	83	78	71	71	78	75	72	N/A	74	69

To illustrate the potential benefits of rigorously investigating the topics presented in this report, a difference map showing the percentage reduction in LCOE between the Current and Advanced Research Technology Scenario is presented in Figure 42. The percent reduction ranges from 9.0% to 32.6%, with an average reduction of 27.5%.

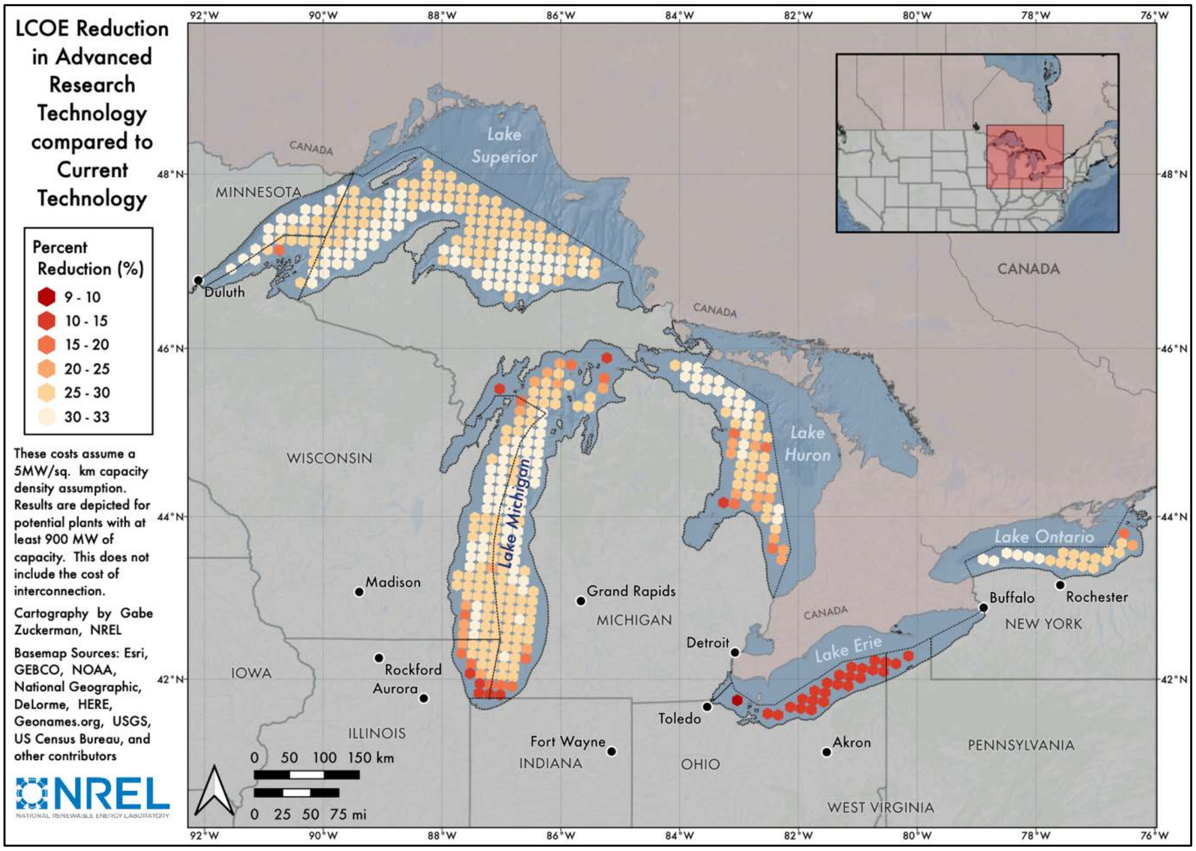

Figure 42. LCOE reductions when using the Advanced Research Technology Scenario compared to the Current Scenario. ***Map from NREL***

10.5 Summary Techno-Economic Analysis

The two scenarios examined in this analysis illustrate the potential for targeted research to reduce the cost of wind energy deployment in the Great Lakes by 2035. According to the modeling methodology outlined in this section, LCOE of Great Lakes wind energy is expected to reach between $75/MWh and $129/MWh by 2035 under the Current Scenario. Under the Advanced Research Technology Scenario, the expected 2035 LCOE range drops between $62/MWh and $89/MWh. The cost is, on average, 27.5% lower for any given location under the Advanced Research Technology Scenario than the Current Scenario. This level of cost reduction is significant and would likely accelerate Great Lakes wind energy deployment while increasing the absolute deployment levels needed by Great Lakes states to meet their decarbonization and clean energy targets.

10.6 Great Lakes Wind Energy Decarbonization Option

One of the fundamental objectives of this study was to assess the conditions under which future large-scale wind energy deployment in the Great Lakes would be needed. A definitive response to this question is beyond the scope of this study (but is recommended for follow-on work) because a comprehensive answer requires a high-resolution assessment of the regional grid including all other energy sources (e.g., land-based wind and solar photovoltaics, and so on), state and federal policy, current and future infrastructure, and many other variables.

The best available data to help shed light on this question were drawn from a 2022 assessment of national decarbonization scenarios conducted using NREL's ReEDS model (Mai et al. 2022). ReEDS is a capacity expansion model that was developed to assess complex trade-offs within the electric grid system. It has an accurate representation of the North American grid infrastructure and long-term evaluations are made by selecting the most favorable technologies to build based on "least cost." It is very useful for understanding sensitivities among many variables and can be prescribed to meet specific targets to assess decarbonization goals.

We were able to garner some limited insights on the large-scale Great Lakes opportunity from the Mai et al. study of the U.S. energy system that assessed national decarbonization targets, and the conditions under which offshore wind energy might play a key role (Figure 43). The infrastructure and capital cost assumptions in Mai et al. are comparable to the Current Scenario used in this report, but these results should not be viewed as a prediction of actual deployment. The Mai et al. study assumptions incorporated many uncertainties about future grid constraints and infrastructure, and many necessary simplifications to make the model function. As such, the analysis does not include recent incentives, such as those outlined in the IRA. Costs for fixed-bottom offshore wind turbines are based on the 2021 ATB "Moderate" scenario, which assumes a 15-MW rated capacity (NREL 2021), but floating offshore wind was not modeled in the Great Lakes by Mai et al. Therefore, all Great Lakes wind energy deployment in Figure 43 was in shallow, fixed-bottom sites which is not representative of the findings of this report. The ReEDS analysis also does not incorporate the region-specific cost adjustments and technology advancements identified in this report. Nevertheless, the Mai study results provide the best-available relative comparison of the interplay among all energy options under various decarbonization scenarios. Updated ReEDS analysis is recommended as a follow-on to this study that would include floating technology and other advancements that could potentially accelerate Great Lakes offshore wind energy deployment or expand the market potential even further.

Figure 43 estimates projected regional deployment of offshore wind energy[18] under a national decarbonization scenario that assumes:

- A 95% reduction in carbon emissions from all sectors, relative to 2005 levels, by 2050
- High electrification from the Electrification Futures Study (Cole et al. 2018)
- A "Limited Access" siting regime for land-based wind energy as described in Lopez et al. (2021)
- New transmission is limited to intraregional only (near the Great Lakes, transmission regions are roughly equivalent to the MISO, PJM, and NYISO control areas)
- State and federal policies—such as renewable portfolio standards and tax credits—as they existed in June 2021.

[18] Although Mai et al. (2022) focuses on offshore wind energy deployment, the study models deployment of a range of resources including land-based wind, solar, energy storage, nuclear, hydrogen, and other renewables.

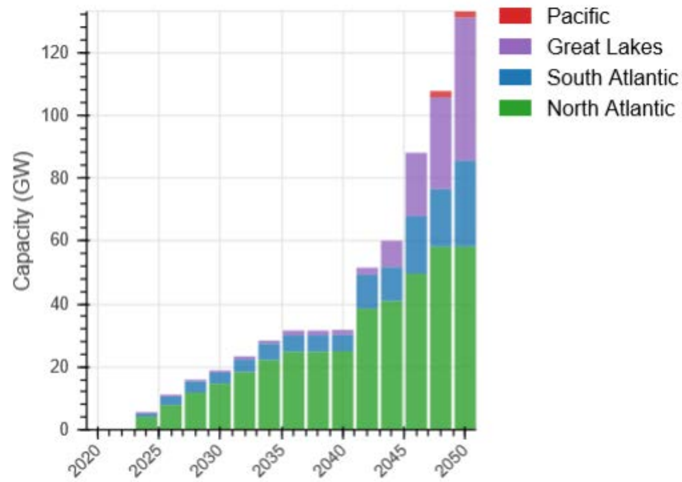

Figure 43. Projected regional offshore wind energy deployment timelines. ***Reproduced from Mai et al. (2022)***

Figure 43 shows that significant Great Lakes wind energy capacity is selected by the ReEDS model between 2044 and 2050, leading to a total of more than 40 GW. While 40 GW is not an accurate prediction of deployment, these results are significant because the late surge in Great Lakes wind energy indicates that, based on the ReEDS modeling assumptions, it eventually becomes the least-cost option. Further analysis is needed, but this suggests that the model exhausts all of its low-cost siting options for land-based wind and solar in the region by the early 2040s, forcing the model to choose Great Lakes wind to meet the 2050 targets.[19] This late surge oindicates that it was the lowest cost relative to the most expensive land-based wind and solar options, but under the Current Scenario these costs would not be optimal and there are many logistical issues that would prevent it from being realized. Under the Advanced Research Technology Scenario, we would expect that the ReEDS model would select Great Lakes wind energy at an earlier year because of the lower costs, resulting in a more feasible deployment scenario that would benefit ratepayers and other stakeholders. This conclusion is not meant to imply that Great Lakes wind energy would have fewer siting constraints than land-based wind and solar; only that the regional resource may eventually become depleted for wind and solar renewables in some locations.

In this study, we consider the logistics required for deployment and for Great Lakes wind energy to provide the most cost-competitive electricity to serve the region's demand. These opportunities emerge under future scenarios that focus on reducing carbon emissions coupled with higher demand for electrification. Moreover, Great Lakes wind can provide low-emissions electricity to the region in scenarios where there are constraints to accessing other low-emissions resources (e.g., land-based wind, solar photovoltaics) due to land use and siting challenges or through barriers to transmission expansion that could bring in low-cost resources from other regions.

[19] Note that this type of extreme deployment of offshore wind did not occur in other regions where a greater diversity of renewable options might be available.

11 Local Stakeholder and Workforce Implementation

11.1 Current Situation

This section builds off preceding sections of the report to bring greater focus to activities that will enhance the readiness to engage with key stakeholders in the region on Great Lakes wind energy, including representatives of tribal nations, disadvantaged communities, local research institutions, local stakeholders, and educational institutions.

In addition to in-depth technical and economic analysis, early and meaningful stakeholder engagement activities will be key to the successful development of Great Lakes wind energy. Stakeholder engagement can help facilitate public input, which is a requirement of many federal, state, and local permitting processes such as NEPA. Stakeholder engagement can also help develop a comprehensive understanding of a project's potential impacts and benefits, lead to better-informed and more equitable decision-making processes, and be linked to higher levels of public acceptance for renewable energy projects (Rand and Hoen 2017). It can also help to organize and prepare sectors to strengthen various aspects of the development process, ranging from supply chain coordination to workforce development initiatives.

The GLWC created a strong foundation for stakeholder engagement efforts in the region. Launched in 2009 as a "multisector coalition of wind energy stakeholders facilitated by the Great Lakes Commission" (Great Lakes Commission 2009), GLWC's multifaceted work included documenting siting principles and guidelines (GLWC 2009), best practices for stakeholder engagement and outreach (GLWC 2011a), and focused stakeholder engagement feedback (GLWC 2013). Although the collaborative ended in 2013, it served as an important starting point on Great Lakes wind energy for many stakeholders in the region and set the precedent that its development will require thoughtful, coordinated engagement with stakeholders across lakes and states.

Stakeholders have also had the opportunity to consider and engage in discussions about the potential for Great Lakes wind energy through state-led processes in the region, beginning with efforts led by New York (New York Power Authority 2010), Michigan (State of Michigan 2009) and Ohio that go back to 2009. Each has elicited feedback from local stakeholders ranging from recreational boaters and fishers to birders, labor unions, community revitalization groups, and climate activists. Workforce development has also been important, as Ohio has pursued Great Lakes wind energy for more than a decade. LEEDCo, the company developing the Icebreaker project in Ohio, has projected that it will have a "$253 million local economic impact and create more than 500 jobs." The governor of Ohio and the chief executive officer of the Cleveland Foundation support the economic development that this project could bring to the region. Some local stakeholders, however, are still reserved about the impacts wind turbines have on local wildlife like bats and birds and want more data to be collected on possible adverse effects (Hancock 2022).

In 2020, the State of New York Public Service Commission directed NYSERDA to revisit the feasibility of wind energy development in the New York state waters of Lake Erie and Lake Ontario (NYSERDA 2022a). To support the development of the New York State *Great Lakes Wind Energy Feasibility Study*, NYSERDA solicited stakeholder input through a series of public webinars and a virtual public feedback session. New York State ultimately decided not to move forward with offshore wind energy in the Great Lakes at this time. While some stakeholders were disappointed with this decision and felt that offshore wind will be essential for power production, other groups felt that that the project risks and costs outweighed the benefits that could be brought to the state (Borrello 2023).

Illinois-led efforts have not been as long-standing but elected officials and community leaders from the southeast side of Chicago, a historically disadvantaged community, responded to a bill in the state's 2022 legislative session by voicing the need to ensure that workforce development takes place in an equitable and locally beneficial manner. Community members emphasized the need for energy developers to formalize local hiring and job training commitments and highlighted the importance of creating programs in local high schools that build skills. In response, labor unions committed to training community members, and a developer shared the possibility of hiring goals being included in a developer's proposal (Chase 2022).

The Great Lakes region is home to many world-class universities and research institutions and has historically been a U.S. manufacturing hub. The availability of supply chain resources and expertise from the already-established industries in the region (e.g., automotive, aerospace, steel, and so on), in addition to access to knowledge makes the region a viable option for expansion of wind energy into the Great Lakes (Shields et al. 2023). According to NOAA (2022), "The total economy for the U.S. Great Lakes region generated $3.1 trillion in gross domestic product while employing 25.8 million people and supporting $1.3 trillion in wages." Involving key players in the development of wind energy in the Great Lakes region will be essential in transitioning successfully to a sustainable future. If stakeholder engagement for Great Lakes wind energy includes disadvantaged communities, the workforce and economic development of the region could increase in a way that is not only adequate in numbers but also equitable in terms of the distribution of the industry's benefits.

Although some representatives of state government, labor unions, and industry have been supportive of the economic development that Great Lakes wind energy could provide, some stakeholder opinions are more cautious of how the industry will affect equitable job placement, the development of training programs, and broader interactions with their viewshed, sense of place, and ecosystem (NYSERDA 2022a; Shea 2022). Identifying key challenges, points of research, and actionable steps to properly engage a range of stakeholders will help the region benefit from wind energy most effectively.

11.1.1 Research Approach

Identifying the key challenge areas and recommended activities for local stakeholder and workforce implementation was preluded by a literature review to gain knowledge surrounding previous relevant work and current prevailing attitudes toward wind energy in the Great Lakes region. We used technical papers, feasibility reports, newspaper articles, and broader internet searches to gather this information. Specifically, the research was focused on:

- Current stakeholder engagement in the broader offshore wind energy industry
- Workforce development in the region and offshore wind industry
- Past work done on the feasibility of wind energy in the Great Lakes

- Current developing opinions of stakeholders in the region on proposed projects.

We then compiled the research collected in these areas into a literature review and conducted an evaluation to determine four key areas that could challenge deployment of wind energy in the region and would benefit from additional investment. One of the major trends noted as a concern for local stakeholders was how workforce development, and access to project development plans, would occur in an equitable way. Additionally, the availability of research done in this space by local research programs appeared to be limited, so identifying research institutions, local industry players, and training programs were all a priority for establishing future actions.

We identified crosscutting activities and tailored them to specific challenge areas. These activities include:

- Stakeholder identification and mapping, including identifying disadvantaged communities with the White House Council on Environmental Quality's Climate and Economic Justice Screening Tool and U.S. Census Bureau (Figure 44 highlights relevant populations identified at a regional level; Figure 45 illustrates populations at the census tract level within the greater Milwaukee, Wisconsin, area as an example of an initial stakeholder mapping effort. It does not include all possible stakeholders).
- Evaluating stakeholder assets, challenges, and opportunities related to understanding and/or engaging in the Great Lakes wind energy development process.
- Research and development strategies to enhance engagement in Great Lakes wind energy through increased coordination and development of priority research and trusted informational resources.

Proactively identifying and preparing to engage key stakeholders in the Great Lakes region will close information gaps, expand workforce opportunities, and integrate equity into the development process. Figure 44 identifies the geographic location of disadvantaged communities and tribal lands in the Great Lakes region, using data from the U.S. Census Bureau and Climate and Economic Justice Screening Tool. The tool uses data sets to identify communities facing burdens related to climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development (Council on Environmental Quality 2023) while recognizing that their spatial representation does not convey their population size. Mapping can serve as a starting point in identifying potential areas where stakeholder engagement and economic development initiatives could occur, but additional research and outreach is recommended to ensure that local perspectives on the characteristics of disadvantaged communities are appropriately understood.

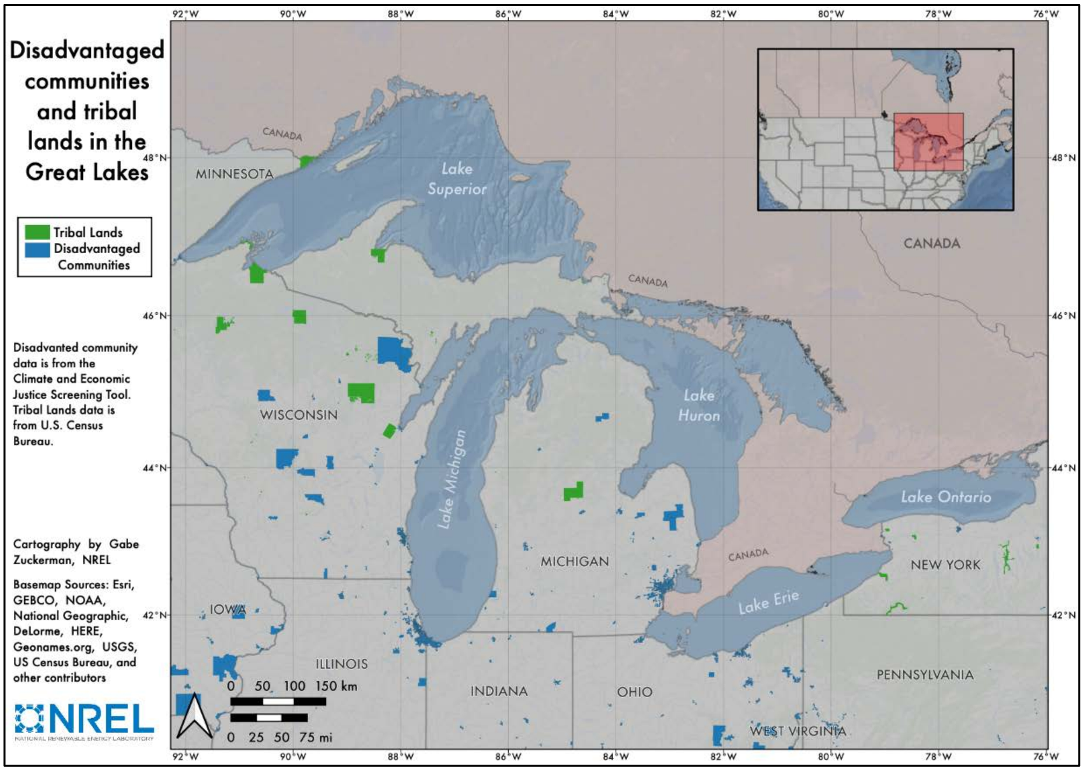

Figure 44. Disadvantaged communities and tribal lands identified in the Great Lakes region. ***Map from NREL***

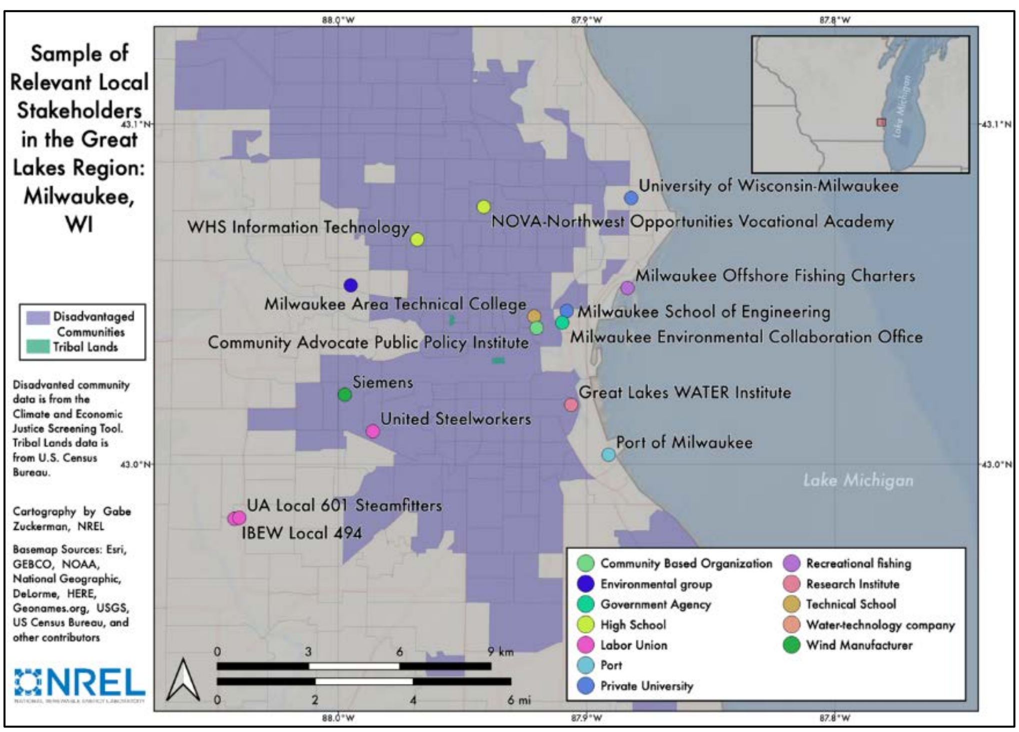

Figure 45. Example of a geospatial stakeholder map in the city of Milwaukee, Wisconsin. ***Map from NREL***

11.2 Key Challenges

11.2.1 Implement Energy Equity and Justice Activities

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	No	No	Yes	Low

Description. More information and purposeful engagements are needed to better understand and prioritize the concepts of energy equity and justice in developing Great Lakes wind energy. The goals of energy equity and justice can be described as "to achieve equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system" (Baker, DeVar, and Prakash 2019). Energy equity includes both the manner in which stakeholders are engaged in decision-making (i.e., procedural equity), as well as how impacts and benefits are defined and allocated (i.e., distributional equity). Great Lakes wind energy will likely need to be developed in a way that is consistent with the Justice40 Initiative's goal of 40% of overall benefits of certain federal investments flowing to disadvantaged communities (The White House 2022). The findings of this effort should subsequently be incorporated across all relevant Great Lakes wind energy activities, rather than be considered as a stand-alone set of issues.

Consequences and impact. Failing to focus on the concepts of energy equity and justice could mean that development of the industry fails to meet emerging state and federal requirements, and that the benefits of Great Lakes wind energy development that could flow to citizens in the region would be minimized and/or distributed in a less-than-equitable manner. This gap could include new jobs being out of reach to members of historically marginalized populations, decision-making taking place without the input of affected stakeholders, and energy infrastructure being sited in overburdened communities. If benefits are distributed in less equitably, historical energy inequalities may be exacerbated, burdening some communities more than others, and public acceptance may be negatively affected. Alternatively, efforts to address energy equity and justice, such as addressing barriers to participation in public process, attentiveness to indigenous interests, and creating targeted job training programs, could ensure alignment with state and federal requirements and ultimately result in more just distribution of benefits from Great Lakes' wind energy and greater societal benefits.

Recommended research activities include:

- Conducting inventory-relevant state and/or federal goals or guidance on equity and justice that will apply to Great Lakes wind energy development (e.g., New York's Climate Leadership and Community Protection Act, Justice40 Initiative) (level of effort: < $200,000, timeline: < 6 months)
- Identifying disadvantaged communities proximate to the Great Lakes region using CEQ's Climate and Economic Justice Screening Tool (consistent with Justice40), any state-level definitions and associated metrics, and input from local stakeholders on how these definitions may resonate or be considered problematic (level of effort: < $200,000, timeline: < 6 months)
- Developing analysis and tools to support eventual appropriate engagement with disadvantaged communities, which includes:

- Conducting literature review and outreach to local stakeholders and tribes to identify best practices for engaging Great Lakes' disadvantaged communities and tribes in wind energy decision-making processes (i.e., procedural equity) as well as identifying/minimizing impacts and identifying/maximizing opportunities for benefit (i.e., distributional equity and related community benefit strategies), while acknowledging the need for tailored plans to appropriately engage different groups (e.g., tribes) (level of effort: \$200,000–\$500,000, timeline: 6 months–1 year)

- Surveying Great Lakes wind energy decision makers to identify opportunities to integrate best practices into stakeholder and workforce engagement activities (in conjunction with activities proposed in Section 9) (level of effort: \$200,000–\$500,000, timeline: 6 months–1 year)

- Developing an evaluation protocol, with input from communities and tribes, that can be used by Great Lakes decision makers to periodically assess engagement efforts with a focus on equity and revising best practice guidance (level of effort: \$200,000–\$500,000, timeline: 6 months–1 year).

11.2.2 Enhance Regional Research Capabilities

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
3	No	No	Yes	Medium

Description. Targeted investment in and coordination of regional research efforts are needed to ensure timely and meaningful progress on the research priorities outlined in this report. The Great Lakes region currently lacks coordinated and comprehensive research efforts and there appears to be a knowledge gap in the local research community about the potential to contribute to this emerging industry. A focused effort to engage with local researchers will enhance their understanding of the industry's potential development path, ensure visibility into the industry's research needs, and highlight the benefits of a more coordinated and substantial regional research effort (e.g., creating a center of excellence, ability to access additional funds).

Consequences and impact. In the absence of a strategic effort to enhance local capacities, Great Lakes wind energy research may be led outside of the region, possibly limiting local buy-in and acceptance. Resulting research may fail to integrate the vast knowledge of local researchers, which could make outcomes more relevant and actionable. As a result, policymakers and other local stakeholders may struggle with incomplete or inaccurate information. Finally, the lack of a coordinated, local research effort may mean that resources are potentially used in duplicative ways, increasing overall costs without moving deployment forward efficiently.

An appropriately resourced and coordinated research effort in the region would position the Great Lakes as leading the deployment of wind energy by maximizing the impact of local research institutions, supporting informed decision-making, and ultimately contributing to realizing economic development and other state or federal goals. A coordinated effort could also result in more efficient distribution of funds to local stakeholders via a centralized funding organization (e.g., NOWRDC), helping to further increase local knowledge and expertise.

Recommended research activities include:

- Mapping research institutions to identify existing entities that are positioned to contribute to the research needs prioritized in this report. Document information such as current activities, comparative strengths, infrastructure assets and needs, and relevant geography, with the results being publicly disseminated to support greater coordination and collaboration efforts in the region (level of effort: <$200,000, timeline: < 6 months).
- Building upon existing local research capacity by preparing to administer solicitations that will enhance coordination and collaboration in the region and conduct new research. Begin by assessing capacity of institutions with a regional presence to facilitate competitive disbursement of funds, entering partnerships to administer funds, and developing a blueprint for how funds will be distributed (level of effort: $200,000–$500,000, timeline: 6 months–1 year).
- Identifying, developing, and using dissemination mechanisms for research as it emerges from coordination and collaboration activities based on identified priority audiences, with a preference placed on existing online resources (e.g., WINDExchange[20]) and taking energy equity findings into consideration (level of effort: $200,000–$500,000, timeline: 3–5 years).

11.2.3 Conduct Formal Coordination To Inform Decision-Making and Stakeholders

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
1	Yes	Yes	Yes	Medium

Description. Building off the efforts highlighted in Section 8, the goal is to identify and engage with key stakeholders to ensure they have access to accurate and relevant foundational information on Great Lakes wind energy development, as well as an ability to provide input on potential impacts and benefits. Integrate energy equity findings (Section 11.2.1) to ensure that the needs and interests of stakeholders representing disadvantaged communities and tribal nations are appropriately considered, but also ensure that other stakeholder groups, such as coastal landowners with viewshed concerns, have access to fact-based, locally relevant information.

Consequences and impact. Social acceptance issues can stem from concerns about unmitigated conflict with environmental and/or human use or local values, lack of information or misinformation, or poor stakeholder engagement processes. These issues can cause significant delays and cost increases to project development (Rand and Hoen 2017). By contrast, centralizing information on key stakeholders, their concerns and priorities, and their needs and

[20] WINDExchange is a platform that is supported by the U.S. Department of Energy to communicate the best-available science and other fact-based information about wind energy to enable U.S. communities to make informed decisions about wind energy development. WINDExchange is currently facilitated by NREL and includes a website (https://windexchange.energy.gov/), a bimonthly e-newsletter, publications, and additional stakeholder resources.

interests in engaging in the development process can improve efforts to create and disseminate informational resources and education/outreach experiences, potentially limiting disruption to project development. This centralized information can also enhance outcomes to be more equitable.

Recommended research activities include:

- Building on existing resources (e.g., past GLWC reports) and proposed Section 8 activities to map key stakeholders who have historically engaged in Great Lakes wind energy discussions or who may have insights into the impacts, benefits, or deployment of resources related to the development of the industry. This activity should include but not be limited to the stakeholder groups identified in Section 8 (e.g., drinking water, recreational and commercial fishing, and viewshed), as well as disadvantaged communities and tribal nations identified earlier in this section (Section 11.2.1), and entities with crosscutting interests (e.g., Great Lakes Commission, relevant state agencies) (level of effort: < $200,000, timeline: < 6 months).
- Building on activities listed in Section 8, this effort will include interviewing key stakeholders to identify top questions, concerns, and priorities related to Great Lakes wind energy development. Comparing a list of topics with available information resources (i.e., survey WINDExchange, research institutions, state agencies) is also needed, as well as identifying gaps where better (i.e., more accurate/up to date, locally relevant, easy to understand) information resources could be created and disseminated. From there, this activity includes integrating findings into other areas of research to increase relevance of work to key stakeholders. For example, for the interests represented in Section 8, this could include visualizing mooring configurations to support discussions and/or trainings with fishers as well as outreach materials on strategies to avoid drinking water impacts or to communicate visual simulation outcomes. For communities, these materials could include research and stakeholder resources to support local stakeholders and developers to identify and design opportunities for equitable community benefit investments (level of effort: $200,000–$500,000, timeline: 6 months–1 year).
- Using feedback from stakeholders and surveys of best practices, this activity will identify and document top strategies for expanding access to priority information. This effort could include conducting local and regional convenings and experiential/interactive engagement activities (e.g., peer to peer, place-based, virtual reality technology), co-creating new resources, and investigating the distinct information/stakeholder needs within the Great Lakes region to avoid generic approaches (level of effort: $200,000–$500,000, timeline: 6 months–1 year).

11.2.4 Perform Workforce Analysis

Priority	Major Deployment Barrier	High Cost Impact	Impacts All Lakes	Level of Knowledge
2	Yes	No	Yes	Medium

Description. One of the major challenges to deploying wind energy in the Great Lakes is ensuring that the workforce of the local region is not only adequate in numbers, but properly trained for careers in the offshore wind energy sector. Acquiring insight into existing training programs, parallel supply chains, industry crossover, and current labor policies will be necessary to properly map the current state of the industry. Mapping the status of the Great Lakes region workforce will allow for a better understanding of the opportunities for the economic development that wind energy can bring to regional residents. Furthermore, ensuring that the workforce analysis is built on a foundation that encourages positive job development in disadvantaged communities will be essential in prioritizing an equitable energy transition.

The Great Lakes region has a variety of industry, manufacturing, and world-class educational and training institutions that could potentially be of benefit to developing the wind energy workforce. Creating a thorough map of the applicable stakeholders in the region could unveil barriers and opportunities in potential workforce training and hiring needs. It would also help policymakers, industry players, and educational and training institutions to plan and incentivize for the future growth of the industry both in training curriculum and supply chain development.

Consequences and impact. Inaction to complete a rigorous analysis of the current and potential workforce related to Great Lakes wind energy development could have adverse effects on the region's ability to meet capacity goals for wind deployment. Insufficient mapping of the status of the industry, training programs, and labor policies in the region could cause overtraining or undertraining in the amount of people entering in the workforce. Conversely, completing a workforce analysis could result in more equitable job creation, economic development for transitional and new industries in the region (leading to a maximization of local job creation), the possibility for exporting to other regions (due to central geography of the Great Lakes), increased knowledge of the Great Lakes region and benefits that wind energy could have there, and the use of existing or new training and education programs.

Recommended research activities include:

- Mapping the current state of workforce training opportunities at educational institutions, including universities, community colleges, certificate programs, unions, and trade schools with programs related to wind or renewable energy development. This mapping activity would include identifying established training programs in the region for jobs related to the Great Lakes wind energy industry, requirements and incentives for attendance to the educational and training institutions, demographics, and the workforce demand that can be met by the currently established educational institutions (level of effort: <200,000, timeline: 6 months−1 year).
- Mapping the current state of workforce occupations, skills, and labor policies. This activity would include identifying job characteristics, classifying contributions from established transitional/parallel industries (e.g., automotive, steel, land-based, cement, and so on), and analyzing the people currently employed in the wind industry or related industry jobs. Additionally, research into active federal, state, and local labor policies and their influence on the Great Lakes wind energy industry would occur (level of effort: <$200,000, timeline: 6 months–1 year).
- Identifying potential opportunities and barriers to deployment of Great Lakes' wind energy. After completing the mapping activities to determine the status of the total workforce, the next step would be to rank the readiness level of the region's ability to support growth in offshore wind energy development. A gaps analysis would then identify opportunities and challenges to deploying wind capacity caused by equitable

workforce development, or lack thereof. In addition to the readiness ranking, a geospatial map of educational institutions, industry players, ports, and disadvantaged communities would be created to help visualize the areas of potential opportunity to develop an adequately trained, diverse workforce. The geospatial map could then be published to help policymakers in the region create effective local policy that could inform further research related to workforce development access needs and highlight opportunities for careers in offshore wind energy for disadvantaged communities (level of effort: $200,000−$500,000, timeline: 1–3 years).

11.3 Desired Outcomes

Collectively, the activities in this section represent an important opportunity to catalyze the development of Great Lakes wind energy by preparing for key stakeholders to engage in and benefit from these efforts. Desired outcomes from this work include:

- Identifying key stakeholders in the region, including those representing disadvantaged communities and those who can help propel workforce development opportunities
- Achieving an enhanced understanding of current stakeholder assets, challenges, and opportunities
- Gaining increased confidence in stakeholder engagement initiatives, supported by best-in-class and locally relevant strategies to engage stakeholders, including those from disadvantaged communities, moving forward.

At this nascent stage, such outcomes could lay a strong foundation of publicly available information from which federal and state agencies, developers, researchers, educators, and local interest groups could benefit. Access to these centralized, shared resources could help jump-start the industry in a way that is tailored to the Great Lakes and regional priorities. In addition, investments in this work may result in:

- Expanding the field of research for freshwater-based wind energy technology (both fixed-bottom and floating foundations) that is relevant in the Great Lakes region and beyond (e.g., through increased research collaborations, contracts, and publications)
- Regional, national, and potentially global research leadership, possibly demonstrated by the creation of a center of excellence within the region
- Targeted investments in workforce development initiatives that leverage existing resources and create opportunity for historically marginalized populations
- Purposeful and inclusive stakeholder engagement efforts that effectively build understanding of locally prioritized issues and encourage participation in decision-making processes.

12 Next Steps and Key Findings

Here, we present the conclusions and necessary next steps for the research topics discussed in this report and key findings for the two crosscutting topics—cost modeling and stakeholder engagement.

Physical Site Characterization

- Freshwater ice presents new challenges relative to ocean-based offshore wind systems because it is stronger than sea ice and occurs uniquely at Great Lakes wind sites. More research is needed to quantify the physical ice environment to enable more robust offshore wind structures that can operate in a freshwater ice environment.
- Better characterization of soils and sediments in the Great Lakes is needed to design substructures that are appropriate for the relatively soft soils, and to address stakeholder concerns around the possibility of reintroducing industrial contaminants into drinking water supplies.
- Improved understanding of daily and seasonal patterns in the wind and waves will help quantify the potential advantages and disadvantages of Great Lakes wind energy relative to other energy resources, including correlation with electricity demand, installation strategies, and design for extreme wind and wave loads.

Infrastructure

- Vessels that can support commercial-scale development of Great Lakes wind energy will be needed. Most existing, conventional offshore wind turbine installation vessels cannot access the lakes due to the dimensions of the locks of the St. Lawrence Seaway, and some of the current vessels would require significant modifications to support wind turbine installation and service operations.
- Ports in the region do not have the capabilities or capacity to support commercial-scale Great Lakes wind energy development. As a result, significant investments will be required, such as expanding quayside space, procuring larger cranes, and dredging the port depth, to allow for Great Lakes wind energy system fabrication, assembly, installation, and operations.

Technology Options

- Great Lakes wind energy systems need an accurate design basis that accounts for the region's unique conditions. The physical environment of the Great Lakes must be accurately characterized so the engineering design tools can be upgraded to model combinations of wind, waves, and ice, especially for extreme conditions.
- Support structure technology will need to be adapted for the Great Lakes environment and several common archetypes used in the ocean will not be suitable for this region. Ice floes and extreme ice ridges will dictate slender columns at the water surface.
- Floating wind systems appear to be quite feasible, but current designs will need to be modified or upgraded to mitigate ice loads. These systems may be the best option in most of the Great Lakes (Lake Erie excluded).

- Siting Great Lakes wind energy projects in deeper water that is farther from shore can minimize many conflicts, such as bat and avian interactions, nearshore ice, viewshed impacts, and disturbance of toxic sediments, but will require floating systems.
- The current fleet of wind turbines that is available at the time of project design will need to be adapted to the Great Lakes environment and the substructures, installation methods, and O&M procedures that are available will need to overcome the vessel constraints of the Saint Lawrence Seaway. Most conventional offshore wind technology will need to be adapted due to the unique environment.

Electric Grid Integration

- Prospective POIs need to be identified for connecting regional Great Lakes wind energy and allowable headroom capacities need to be quantified, both with the existing regional system and planned upgrades.
- Recommended electrical infrastructure upgrades need to be defined and quantified in support of potential Great Lakes wind energy development for both transmission and interconnection equipment, including existing plant retirement impacts.
- Interarray and transmission cable design, installation and maintenance practices need to be assessed, focusing on additional requirements posed by potential ice interactions.
- Floating wind turbine and substation design solutions that account for the protection of the dynamic cables and mooring lines against extreme ice floes are needed.

Wildlife and Environment

- The potential effects of Great Lakes wind energy activities on wildlife, habitat, and ecosystems need to be assessed and mitigated as early as possible in the planning process.
- Given relatively high concentrations of bats and birds in the region, a combination of baseline and postconstruction studies are necessary to determine the activity patterns of bat and bird movement across the Great Lakes.
- The potential effects of multiple stressors associated with Great Lakes wind energy development on aquatic species, habitat, and environmental processes need to be assessed through relative risk assessments, data collection, and modeling.

Human Use

- The potential effects of Great Lakes wind energy on the viewshed of people living, working, and recreating in the region need to be assessed to better understand and minimize those effects.
- Potential risks to the drinking water supply need to be assessed and safe practices for Great Lakes wind energy deployment need to be identified to maintain clean water in the region.
- Strategies need to be developed to ensure that Great Lakes wind energy can successfully coexist with commercial and recreational fishers. These strategies must aim to understand fishing methods, requirements, and means of minimizing impacts.

Regulatory and Policy

- For each affected Great Lakes state, a thorough review is needed of offshore leasing processes, and the major federal, state, and utility permitting and regulatory authorizations that would likely be required for wind energy projects in a state's territorial waters.
- A suite of environmental and international laws will apply to Great Lakes wind energy development, which will need to be understood and assessed to help standardize and streamline the permitting process.
- Infrastructure and physical regulations must be assessed to identify existing restrictions and requirements and anticipate those that have not been articulated, including restrictions and requirements related to interconnection, dredging, ports, vessels, and radar.

12.1 Crosscutting Topics

The key findings for the crosscutting topics are as follows.

Cost modeling

- Research and development that addresses regional challenges and enables Great Lakes wind energy to take advantage of economies of scale can potentially reduce the LCOE by close to 30% in 2035 compared to a scenario without targeted research and development.
- Both fixed-bottom and floating technologies can achieve LCOE below $80/MWh in 2035 under the Advanced Research Technology Scenario.
- Preliminary capacity expansion modeling results indicate that Great Lakes wind energy might be needed for scenarios of 95% decarbonization in the region.

Stakeholder Engagement

- There are a wide range of stakeholders and tribes throughout the Great Lakes who can help shape the future of wind energy in this region. Some of these stakeholders have a history engaging in the issue; some are just beginning to engage and coordinate.
- Proactively preparing for expanded engagement and coordination with key stakeholders throughout the region—including members of disadvantaged communities and leaders of tribal lands, research institutions, users of the lakes, and workforce development catalysts—can better position the industry for development by ensuring these stakeholders can effectively participate in and contribute to the process.
- Building on past efforts and best practices, investment in future stakeholder activities can ensure that targeted, regionally informed approaches are used to engage stakeholders in meaningful and equitable ways as well as expand the benefits of Great Lakes wind energy. Activities include mapping and interviewing stakeholders; evaluating their assets, challenges, and opportunities; and developing strategies that enhance engagement and increase coordination.

13 Suggested Next Steps

This study indicates that the adoption of wind energy could enable states in this region to pursue their clean-energy goals while bolstering their economies with high-paying jobs and providing a cleaner environment for the local residents. The Great Lakes have an abundant wind resource near coastal population centers, and there is a real opportunity for it to contribute to the regional energy mix.

To develop an informed Great Lakes wind energy strategy, further investments in targeted research are needed by federal and state agencies, including through strategic partnerships. There is a need to implement a research plan to address the high-priority topics outlined in this report through the various funding mechanisms available (e.g., competitive solicitations, direct funding opportunities, and so on) and multiagency collaborations. For example, further studies are needed on the economics of fixed and floating wind deployment in each of the lakes, along with the other research recommended in this report. A helpful step toward implementing the identified research activities would be for DOE to consider issuing a request for information to gather feedback from stakeholders and tribes in the communities to further inform a Great Lakes wind energy research agenda.

Understanding the implications of quickly evolving state and federal policies will be a necessary step toward determining the potential feasibility of wind energy deployment on each lake. For example, the IRA contains multiple provisions for offshore wind energy, which could help incentivize Great Lakes wind energy development, including considerations for transmission planning, investment tax credits, and domestic supply chain development.

Lacking regulatory leadership at the regional level or a central organizing body that has been mandated by law to regulate the development of these wind energy resources, there is a need for regional planning and coordination efforts to efficiently develop the technology where appropriate. Consideration should be given to forming a Great Lakes wind energy advisory group, with members from the government (state and federal), research, nongovernmental organizations, and industry sectors. The Bureau of Ocean Energy Management and Bureau of Safety and Environmental Enforcement should be invited as key advisors to provide lessons learned from Outer Continental Shelf waters with potential application to the Great Lakes region.

We also recommend that a workshop be organized and held to encourage information dissemination and exchange among key stakeholders. The main goals would be to initiate a dialogue among states, prioritize research topics, and encourage regional partnerships. The workshop agenda could be informed by similar activities of the Outer Continental Shelf renewable energy intergovernmental task forces and their regular meeting agendas. Two-day workshops could be held, possibly in two separate sessions to recognize common geographic interests: perhaps one for the western and one for eastern regions of the Great Lakes. The western region could include Minnesota, Wisconsin, Illinois, Indiana, and Michigan (Lake Superior, Lake Michigan, and Lake Huron), and the eastern region could include Michigan, Ohio, Pennsylvania, and New York (Lake Erie and Lake Ontario). Note that Michigan is proposed for inclusion in both regional workshops given its location and the number of lakes that it borders. The workshop agenda would include presentations based on the existing knowledge base and discussions led by each state representing their interests for the best path forward.

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