Meshed Offshore Wind Transmission Study

Final Report | Report Number 24-23 | April 2024

NEW YORK STATE | NYSERDA

NYSERDA's Promise to New Yorkers:

NYSERDA provides resources, expertise, and objective information so New Yorkers can make confident, informed energy decisions.

Our Vision:

New York is a global climate leader building a healthier future with thriving communities; homes and businesses powered by clean energy; and economic opportunities accessible to all New Yorkers.

Our Mission:

Advance clean energy innovation and investments to combat climate change, improving the health, resiliency, and prosperity of New Yorkers and delivering benefits equitably to all.

Meshed Offshore Wind Transmission Study

Final Report

Prepared for:

New York State Energy Research and Development Authority

Albany, NY

David Coup
Assistant Director, Policy, Analysis and Research

and

New York State Department of Public Service

Albany, NY

Leka Gjonaj
Chief, Electric Safety and Reliability

Prepared by:

Quanta Technology LLC

Raleigh, NC

Rahul Anilkumar, Transmission and Regulatory
Director

Branka Nirenberg
Senior Project Manager, Transmission and Regulatory

NYSERDA Report 24-23 NYSERDA Contract 184885 April 2024

Notice

Preferred Citation

New York State Energy and Research Development Authority (NYSERDA). 2024. "Meshed Offshore Wind Transmission Study." NYSERDA Report Number 24-23. Prepared by Quanta Technology, LLC, Raleigh, NC. nyserda.ny.gov/publications

Abstract

The study evaluated the benefits, costs, and challenges associated with different offshore transmission expansion pathways. New York State meshed transmission and interregional network configurations were analyzed and compared against radial transmission configurations.

Keywords

Offshore wind, meshed transmission, radial transmission, networked transmission, inter-regional transmission, injection, transmission.

Acknowledgments

Special thanks to the following people for their expertise, collaboration, and support in completing this study: Ross Altman (New York Independent System Operator), John Bernecker (NYSERDA), Greg Brinkman (National Renewable Energy Laboratory), Laila El-Ashmawy (NYSERDA), Greg Lampman (NYSERDA), Yachi Lin (NYISO), and Kate McClellan Press (NYSERDA).

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

A	ampere
AC	alternating current
APC	adjusted production cost
BCA	benefit/cost analysis
BTM-PV	behind the meter photovoltaics
CAC	New York State Climate Action Counsel
Capex	capital expenditures
Climate Act	Climate Leadership and Community Protection Act
DC	direct current

DOE	United States Department of Energy
DPS	New York State Department of Public Service
FERC	Federal Energy Regulatory Commission
GIS	gas-insulated switchgear
GW	gigawatt
GWh	gigawatt-hours
HQ	Hydro Quebec
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IESO	Independent Electricity System Operator
ISO	independent system operator
ISO-NE	Independent System Operator New England, Inc.
kV	kilovolt
LBMP	location based marginal price
LTC	load tap control
M$	millions
MVA	megavolt ampere
MW	megawatts
MWh	megawatt hour
NPV	net present value
NYCA	New York Control Area
NYISO	New York Independent System Operator, Inc.
NYSERDA	New York State Energy Research and Development Authority
O&M	operations and maintenance
OREC	offshore renewable energy credit
OSW	offshore wind
P&C	protection and controls
POIs	points of intersection
PJM	Pennsylvania-Jersey-Maryland interconnection
SCADA	supervisory control and data acquisition
VSC	voltage source converter
WEA	wind energy area

Summary

In the January 20, 2022, New York Public Service Commission (Commission) Order on Power Grid Study Recommendations, the Commission recognized the potential benefits of creating a shared "meshed" offshore transmission system to handle energy injections from multiple offshore wind (OSW) generating projects and directed the New York State Department of Public Service (DPS) staff to coordinate with the New York State Energy Research and Development Authority (NYSERDA) to study the relative benefits, costs, and challenges associated with a meshed OSW transmission system.[1] The order also required future OSW generation proposals to be designed with the optional capability to interconnect with a meshed system if the Commission were to recommend such configurations.

This study responds to the Commission's directive. It explores the benefits and costs of potential offshore transmission configurations designed to accommodate 20 gigawatts (GW) of OSW delivered to New York State interconnection points, as compared to a radial expansion strategy. The 20 GW envelope was informed by the integration analysis developed for the New York State Climate Action Council (CAC) Draft Scoping Plan,[2] which included scenarios with upward of 20 GW of OSW being deployed.

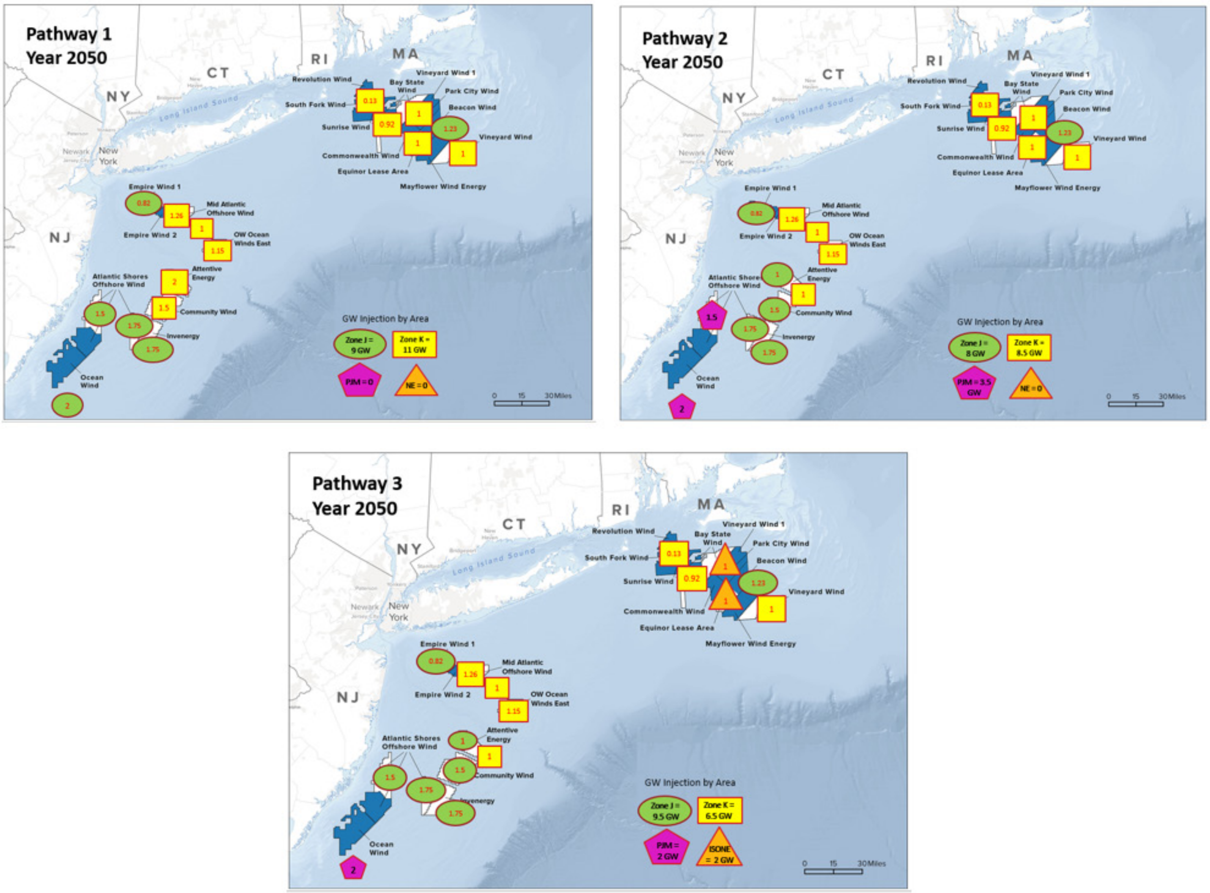
The study used a pathway-based approach to study the benefits, costs, and challenges associated with different offshore transmission expansion pathways. Both New York State–meshed and interregional network configurations were analyzed. Meshed offshore transmission elements were designed to be consistent with NYSERDA's Meshed-Ready Technical Requirements applicable to OSW generation.[3]

The analysis and conclusions presented herein were derived through a combination of analytics that include scenario development, power flow analysis, production simulation studies, Monte Carlo simulations, and benefit/cost analysis. The models and analytics were baselined against the outcomes from the CAC Draft Scoping Plan (Scenario 3), previous NYSERDA filings, and information from transmission vendor partners. The modeling and analysis were derived through an iterative process that included technical studies and economic analysis. The technical studies resulted in the determination of illustrative onshore points of interconnection (POIs) and offshore meshed grid designs. The analysis included reliability analysis and transmission expansion studies. The economic analysis included the derivation of cost estimates, benefit calculations, and economic simulations.

Three illustrative pathways were developed to analyze OSW energy deployment with corresponding transmission topology (such as radial lines, regional meshed system, or interregional network) build-out and sequencing in U.S. Atlantic waters between 2035, 2040, and 2050. The onshore generation and storage resources were the same for all three pathways and were informed by the CAC Draft Scoping Plan, Scenario 3. The pathways included a range of plausible POIs, wind energy areas (WEAs), offshore transmission connections, onshore network upgrades, and cable routes.

Each pathway represents an illustrative combination of diverse OSW deployments across New York City, Long Island, and external neighbors (Pennsylvania-Jersey-Maryland [PJM] and Independent System Operator – New England, Inc. [ISONE]). The primary difference among the pathways is the allocation of OSW energy to the different mainland injection points. Figure S-1[4] presents a visual depiction of the 2050 OSW deployments across all three pathways and the diversity in distribution of capacity between areas under study. Each of these illustrative WEA combinations was studied with radial only and meshed/networked offshore transmission. Owing to the diverse nature of the pathways, they are not comparable to one another but allow for an independent evaluation of a range of illustrative pathways for OSW deployment. They are not directly comparable because each pathway includes OSW injections to a different geographic mix of regions and POIs onshore.

Figure S-1. Offshore Wind Pathway Outcomes by 2050



The results of the study indicate that, across all pathways, meshed configurations yield benefit/cost ratios higher than 1.5 compared to radial configurations.[5] Production cost savings, which translate into ratepayer cost savings, account for the largest volume of benefits and exceed the incremental costs of the meshed designs.

Additional benefits include reduced curtailment during onshore and offshore grid events. The benefits from meshed configurations were prominent during offshore grid events, including scheduled and forced outages of offshore grid infrastructure (due to maintenance, equipment failure, or catastrophic events, e.g., ship anchor drag).

Also, the offshore meshed grid infrastructure creates alternative paths for OSW to directly reach the load centers, reducing the stress on existing onshore infrastructure. In particular, the study indicates that meshed infrastructure may reduce the number of onshore cables needed between Zone K and the rest of the State.

The cost of meshed grid infrastructure was estimated to be $99 million per WEA, with the cost of meshing cables at approximately $4.5 million per mile. These costs represent the difference in investments made between radial and meshed configurations. All other elements, including onshore facilities, interconnection costs, and system upgrades, were established to remain the same until modeling could determine whether a meshed transmission configuration might allow some upgrades to be avoided.

Importantly, the benefits were evaluated with power flowing from the OSW farms to onshore POIs. Power was not assumed to be able to flow from onshore POIs out to the offshore network because of current market structures. The benefits are expected to be more significant if bidirectional flow capabilities between the OSW farms and different POIs are considered in the future. The "Atlantic Offshore Wind Transmission Study"[6] demonstrated significant additional benefits due to bidirectional flow for an interregional offshore network.

While the three pathways represent unique trajectories, the results indicate positive performance improvements with meshed transmission across all three:

- **Adjusted production cost savings:** Each of the three pathways observed $242 million, $584 million, and $493 million in adjusted production cost savings, respectively, in 2050. Additionally, curtailments for the year 2050 alone were reduced to 1,362 gigawatt-hours (GWh) (21% reduction), 2,690 GWh (50% reduction), and 300 GWh (9% reduction), respectively.
- **Increased availability:** Each of the three pathways avoided approximately 170 GWh to 190 GWh of curtailment due to offshore grid events (i.e., scheduled and forced outages) in the year 2050. The avoided curtailments in 2050 alone resulted in a range of savings of $42 million to $53 million.
- **Avoided onshore transmission costs:** Across each of three pathways avoided, investments in onshore upgrades of $500 million of onshore upgrades were avoided by 2050 because the offshore meshed grid infrastructure creates alternative paths for offshore wind to directly reach the load centers, reducing the stress on existing onshore infrastructure. In particular, the study indicates that meshed infrastructure may reduce the number of onshore cables needed between Zone K and the rest of the State.

Benefit/cost analysis was performed using a levelized real cost approach to cover the investment horizon until 2080, which includes replacement of assets every 30 years, and operations and maintenance (O&M) costs estimated at 1% of the capital expenditure (Capex). The benefits were extended across the asset's lifetime by carrying the 2050 benefits until 2080. Table S-1 presents the summary of findings from each pathway. As stated earlier, each pathway represents a unique, illustrative trajectory to 20 GW of OSW deployments.

Table S-1. Summary of Benefits and Costs by Pathways

All in 2020 Dollars	Pathway 1	Pathway 2	Pathway 3
NPV of Benefits ($M)	3,928	7,637	6,821
NPV of Levelized Total Costs ($M)	2,333	2,406	2,377
Benefit/Cost Ratio	1.7	3.2	2.9

In addition to all the pathways demonstrating favorable benefit/cost ratios, the levelized cost analysis indicated the annualized benefits exceed the annualized investment costs within eight years of the first investment for all pathways. These findings further highlight the potential value of a regional and interregional meshed system. The build-out of interzonal meshed transmission would be a key consideration in extracting significant benefits from future meshed grid configurations. Interzonal meshed designs enhance the efficiency of the system through the locational diversity of interconnection points, so that whenever zonal price separation occurs between the onshore POIs, the meshed offshore system can provide congestion relief by providing options for where OSW can be injected among the networked POIs.

An additional scenario was studied that leverages an interzonal meshed design but limits the OSW build-out to New York State's current 9 GW OSW goal over the horizon years 2035, 2040, and 2050. The analysis indicates a benefit/cost ratio of 1.6 compared to the radial model, demonstrating a potentially favorable outcome.

Considering the complexity of offshore meshed transmission grids, technological advancements, and risks and uncertainties in future grid conditions, the study identifies several areas for further investigation. Next steps include determining how procurement contracts and strategies can be informed by the findings of this study and support the realization of benefits. Certain areas, such as the standardization of network-ready equipment and development of reliability criteria, require coordinated near-term actions to advance offshore meshed transmission grid further. Addressing these challenges is key to realizing the full scope of benefits identified in this study and potentially enabling greater benefits in the future. Also recognized is that an incremental cost is associated with these actions.

The work suggests that addressing the following focus areas would contribute to the realization of the identified benefits:

- NYISO market and operations issues
- Interregional market and operations issues

- Network-ready equipment standardization and high-voltage direct current (HVDC) technical issues
- Reliability criteria
- Other regulatory issues

The key stakeholders whose commitment to the effort will be necessary include the states that will participate in and benefit from an interregional system, the New York Independent System Operator, Inc. (NYISO), other regional system operators, interstate collaboratives, the U.S. Department of Energy, and the Federal Energy Regulatory Commission (FERC).

1 Background

New York State has taken several steps to plan for the transition to a zero-carbon electric system contemplated under the State's landmark Climate Leadership and Community Protection Act (Climate Act). In January 2021, New York State Energy Research and Development Authority (NYSERDA) and New York State Department of Public Service (DPS) published a power grid study that includes a report on local transmission and distribution upgrades necessary to achieve Climate Act targets; a study of offshore and onshore bulk power transmission infrastructure scenarios, and related environmental permitting considerations, to illustrate possible solutions to integrate the mandated 9,000 megawatts (MW) of offshore wind (OSW); and an analysis of transmission, generation, and storage options for achieving 70% renewable generation by 2030, and a zero-emissions grid by 2040.

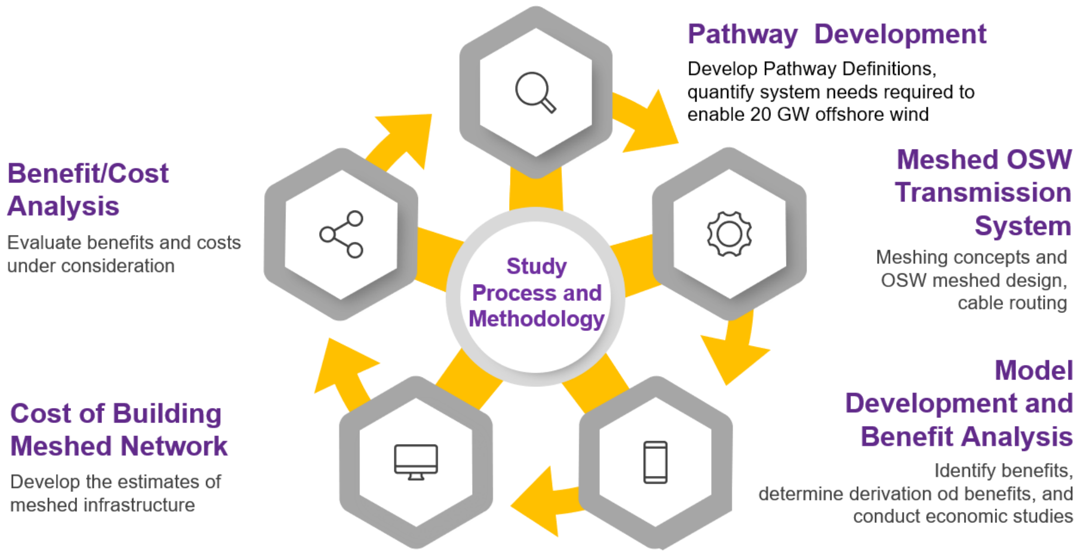
On January 20, 2022, DPS Commission Order on the Power Grid Study Recommendations,[7] the Commission recognized the potential benefits of creating a shared meshed offshore system to handle energy injections from multiple OSW generating projects. Such an approach would contrast with what has to date been the most common approach for interconnecting OSW resources, individual (radial) generation ties. Under the radial configuration, projects are interconnected individually to the onshore electricity grid through dedicated cables, either using high-voltage alternating current (HVAC) or high-voltage direct current (HVDC) equipment. The meshed design contemplated in the order links the offshore substations of individual OSW projects with each other to form a network.[8] The Commission directed DPS staff to work with NYSERDA on a study of the relative benefits, costs, and challenges associated with implementing meshed OSW transmission system. The Commission also directed NYSERDA to require that future OSW proposals be designed with the optional capability to interconnect with a meshed system if the Commission were later to recommend such configurations.

Consistent with the Commission order, the overall objectives of this study are to:

- Evaluate costs and benefits of potential New York State meshed and interregional network OSW transmission configurations to connect varying levels of OSW delivered to New York State by 2050.
- Use a scenario-based approach that considers reasonable and plausible pathways based on the 20 GW OSW deployment levels suggested in the Climate Action Council (CAC) Integration Analysis.
- Support the comparative evaluation between radial and meshed system configurations. Perform a benefit/cost analysis using a combination of technical and economic studies.

Figure 1 provides a high-level overview of the study process and methodology.

Figure 1. Study Process and Methodology



Given the scale and complexity of the offshore meshed design, importantly, the pathways do not represent a specific blueprint, but rather represent indicative pathways and findings to support future OSW planning.

The remainder of this report summarizes and discusses the Pathway Development (section 2), the Meshed OSW Transmission System (section 3), Model Development and Benefits (section 4), Cost of Building Meshed Networks (section 5), Benefit/Cost Analysis (section 6), and Findings and Recommendations (section 7). Appendix A provides further insight into the technical elements of the analysis, including the benefit categories across the lifetime of assets and pathways under evaluation; appendix B provides a detailed analysis of the curtailment reductions for all three pathways; appendix C contains additional details related to the production cost modeling results for the three pathways; and appendix D includes additional information related to the scenario where only the current 9 GW OSW target is achieved.

2 Pathway Development

The first step in the study process was to develop a range of illustrative pathways for OSW development and grid connection. Future levels of the OSW deployment, the land-based resource mix, and the electric demand portfolios for New York State and neighboring regions were drawn from the CAC's Draft Scoping Plan, Scenario 3. The onshore resource mix and electric demand portfolios were disaggregated from zonal to nodal representation using information from independent system operator (ISO)–specific outlook studies, state specific policy objectives, and interconnection queues.

Three pathways for OSW generation, and associated transmission, were identified. The OSW deployments for all three were phased across the years 2035, 2040, and 2050 at 9 GW, 15 GW, and 20 GW, respectively. Each pathway uses a different combination of points of interconnection (POIs) within different New York State zones and neighboring regions, WEAs, and project meshing combinations. Of course, the future grouping of these parameters is unknown, so the study sought to create a set of illustrative combinations to test the potential benefits of meshed transmission across a diverse range of potential situations. The pathways were informed by additional sources of information including:

- Potential locations of awarded and future OSW projects[9]
- NYSERDA Offshore Wind Cable Corridor Assessment[10]
- Proximity of adjacent OSW projects
- NYSERDA Meshed-Ready Technical Requirements[11]

The next section describes how these sources were combined to create the pathways.

2.1 Selection of a Geographically Diverse Mix of Offshore Wind Injection Locations

To begin developing the pathways, a geographically diverse mix of OSW injection locations was developed for New York State (Zones J and K) and for neighboring regions.

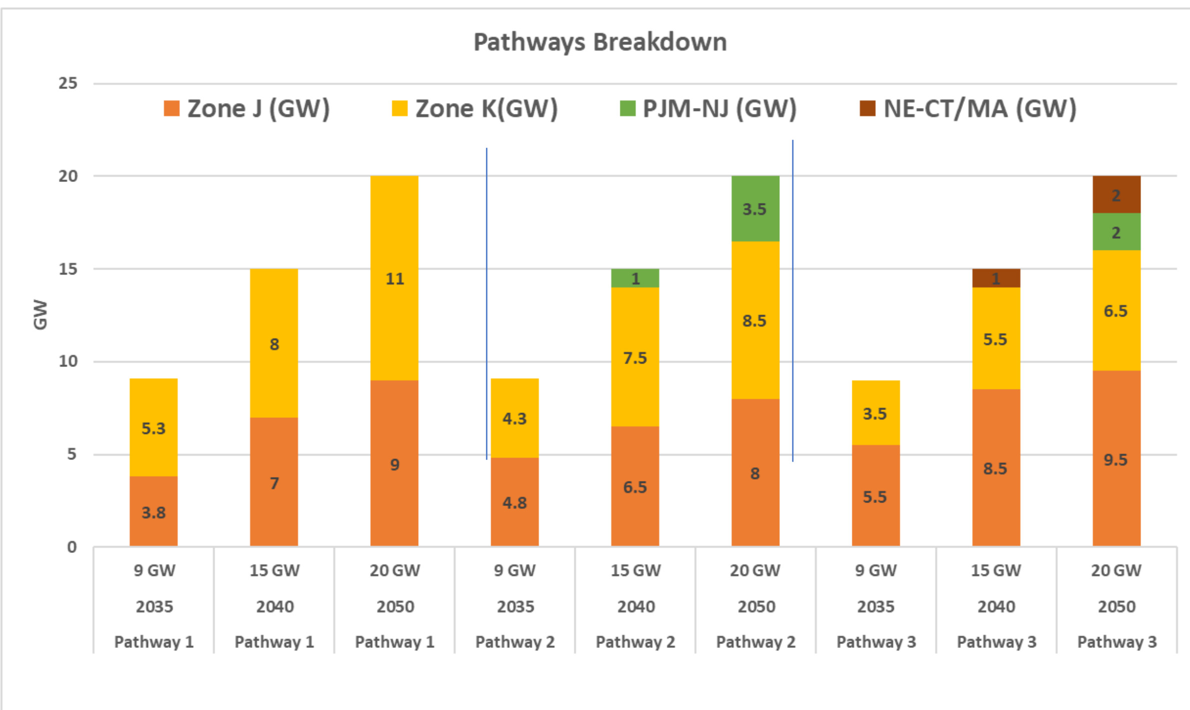
- Pathway 1
  - Assumes all OSW is injected directly into the New York Stae grid with more OSW going to Long Island (Zone K) than to New York City (Zone J)
- Pathway 2
  - Has balanced injections of OSW to Zones J and K
  - Includes injection of OSW into PJM

- Pathway 3
  - Has more OSW injected to Zone J than Zone K
  - Includes injections into PJM and ISO-NE

In Pathways 2 and 3, where illustrative interregional networks for offshore transmission were evaluated, the study assumed that New York State procured the OSW projects injected into neighboring states to be consistent with the CAC Draft Scoping Plan, Scenario 3, which complies with the Climate Act. Injections into ISO-NE and PJM were analyzed for deliverability to the New York Control Area (NYCA), as required by section 2.1.6 of the ORECRFP23-1 Request for Proposals in 2023. The deliverability studies were performed in accordance with PJM Generation Deliverability procedures outlined by PJM Manual 14B and ISO-NE Planning Procedures and ISO-NE Planning Procedure 10. The resulting illustrative transmission expansion portfolio was included into each respective pathway.

Figure 2 illustrates the geographical mix of OSW injection locations in the three pathways.

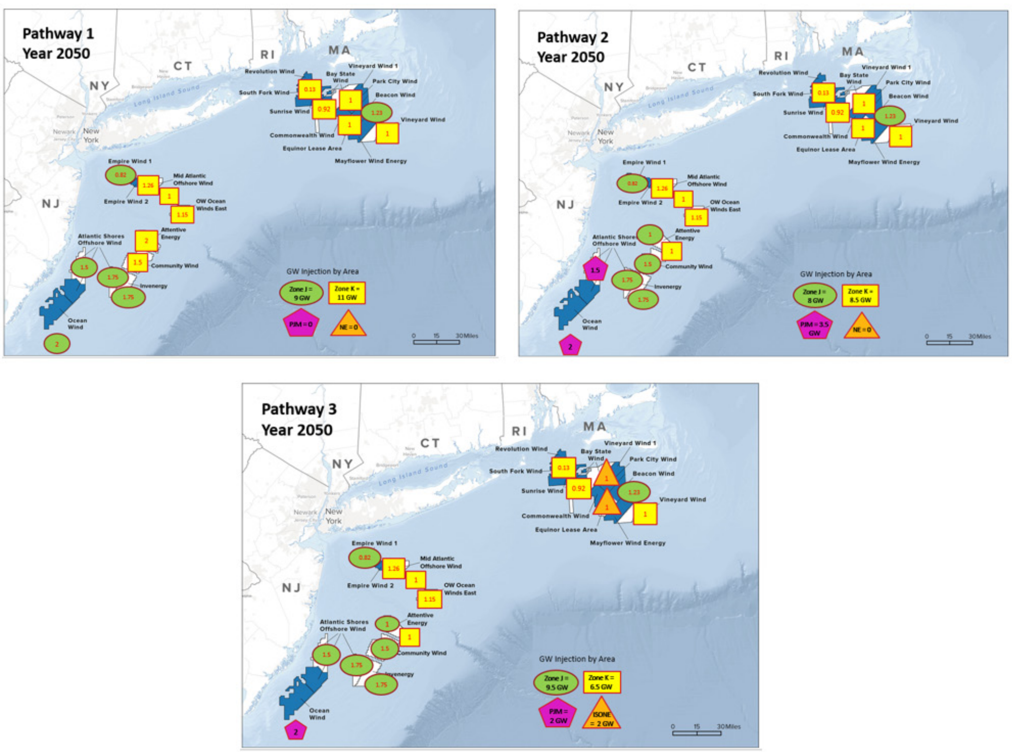
Figure 2. Pathways by Zones/Regions



2.2 Identification of Offshore Wind Energy Areas

Offshore wind energy areas (WEAs) that could plausibly complement the build-out of up to 20 GW of OSW were then identified. This evaluation considered the capacity of all WEAs in the northeastern United States previously auctioned and under development at the time that the analysis began. It also considered adding capacity to projects currently in development. Importantly, this analysis does not consider competition for capacity from Massachusetts, Connecticut, Rhode Island, or New Jersey. The selected WEAs are consistent across all pathways and are intended to support the creation of a diverse set of illustrative outcomes for the analysis, as depicted in Figure 3.

Figure 3. Wind Energy Areas for Each Pathway



2.3 Identification of Onshore Points of Interconnection

The study identified POIs through an optimized screening process that evaluated available headroom from each substation in the New York City area, Long Island, PJM, and ISO-NE. The study used a combination of power flow and production-cost studies to identify POIs with the least contribution toward onshore network upgrades. Following the analysis, 17 substations were identified with the ability to accommodate OSW capacities varying from 1 GW to 2 GW.[12]

The substations were distributed across pathways to meet the selected OSW distribution mix among Zone J, Zone K, PJM, and ISO-NE described earlier. Some solutions involved creating new interties between NYISO and neighbors to support out-of-state injections. The combination of POIs and illustrative onshore upgrades are the same for each pathway's radial and meshed transmission configurations. As Table 1 shows, the combination of POIs was representative of future hub locations and supported a diverse range of multiple POIs.

Table 1. Offshore Wind Deployment Scenarios for 2050

Dark cells identify the selected POIs.

Point of Interconnection	Landing Point	Pathway 1	Pathway 2	Pathway 3
Gowanus	Zone J	■	■	■
Astoria	Zone J	■	■	■
W 49th Street	Zone J	■		
Mott Haven	Zone J	■		■
Farragut West	Zone J	■	■	■
Ravenswood/Vernon	Zone J	■		■
Holbrook	Zone K	■	■	■
Shore Road	Zone K	■	■	■
Ruland Road	Zone K	■	■	■
EGC	Zone K	■	■	■
Newbridge	Zone K	■	■	
Barrett	Zone K	■	■	■
South Fork	Zone K	■	■	■
Northport	Zone K	■	■	
Goethals	Zone J		■	■
Academy	Zone J		■	
Rainey East	Zone J		■	■
Deans	PJM		■	■
Middlesex	PJM		■	
West Farnum	ISO-NE			■
Kent County	ISO-NE			■

2.4 Cable Corridor and Routing

The WEAs and onshore POIs were evaluated to identify feasible routes and landing areas to connect OSW power with onshore substations. Supporting the analysis was NYSERDA's OSW Cable Corridor

Assessment. The findings from the study were used to develop representative offshore route corridors between OSW lease areas and the nearshore coastal region of New York State (i.e., landing sites along the New York State coast). Onshore route segments extended from the shore landing sites to the identified POIs. The illustrative cable routes were the same in both the radial and meshed versions of each pathway.

2.5 Offshore Wind Connection Technologies

The HVDC technology was analyzed as the transmission solution to deliver offshore power to onshore. The estimated headroom at onshore POIs were used to guide the sizing of the HVDC technology, including 320 kilovolts (kV), 400 kV and 525 kV technology. The project team included feedback from manufacturer partners Hitachi Energy, NKT Inc, and Aibel to support the technology assessment and selection. The analysis included 320 kV technology for up to 1,200 MW OSW projects, 400 kV technology for up to 1,600 MW OSW projects, and 525 kV technology for up to 2,000 MW OSW projects.

2.6 Offshore Wind Connection Concepts

The analysis considers radial and meshed grid configurations. Under the radial connection concept all OSW projects will be connected to the grid separately using dedicated lines. The meshed grid configuration is adopted from NYSERDA's Meshed-Ready Technical Requirements, which section 3 of this report describes.

Using the process described earlier, a unique combination of resource interconnection points, OSW distribution, onshore transmission, and interregional transmission layouts is associated with each pathway. The information was used to develop power flow models that represent varying loading conditions and production cost simulation models. Each unique case was evaluated with both OSW connection concepts—radial and meshed. The differences between the two were used to estimate benefits.

The three pathways are not directly comparable because each includes a different geographic mix of injections to different regions and POIs onshore (and the associated onshore upgrades). However, this group of pathways does allow for the assessment of the potential benefits of meshed transmission across a diverse range of situations.

In addition, a pathway was also considered where only the current New York State goal of 9 GW of OSW by 2035 is deployed and sustained in 2040 and 2050. Appendix D has details about this pathway.

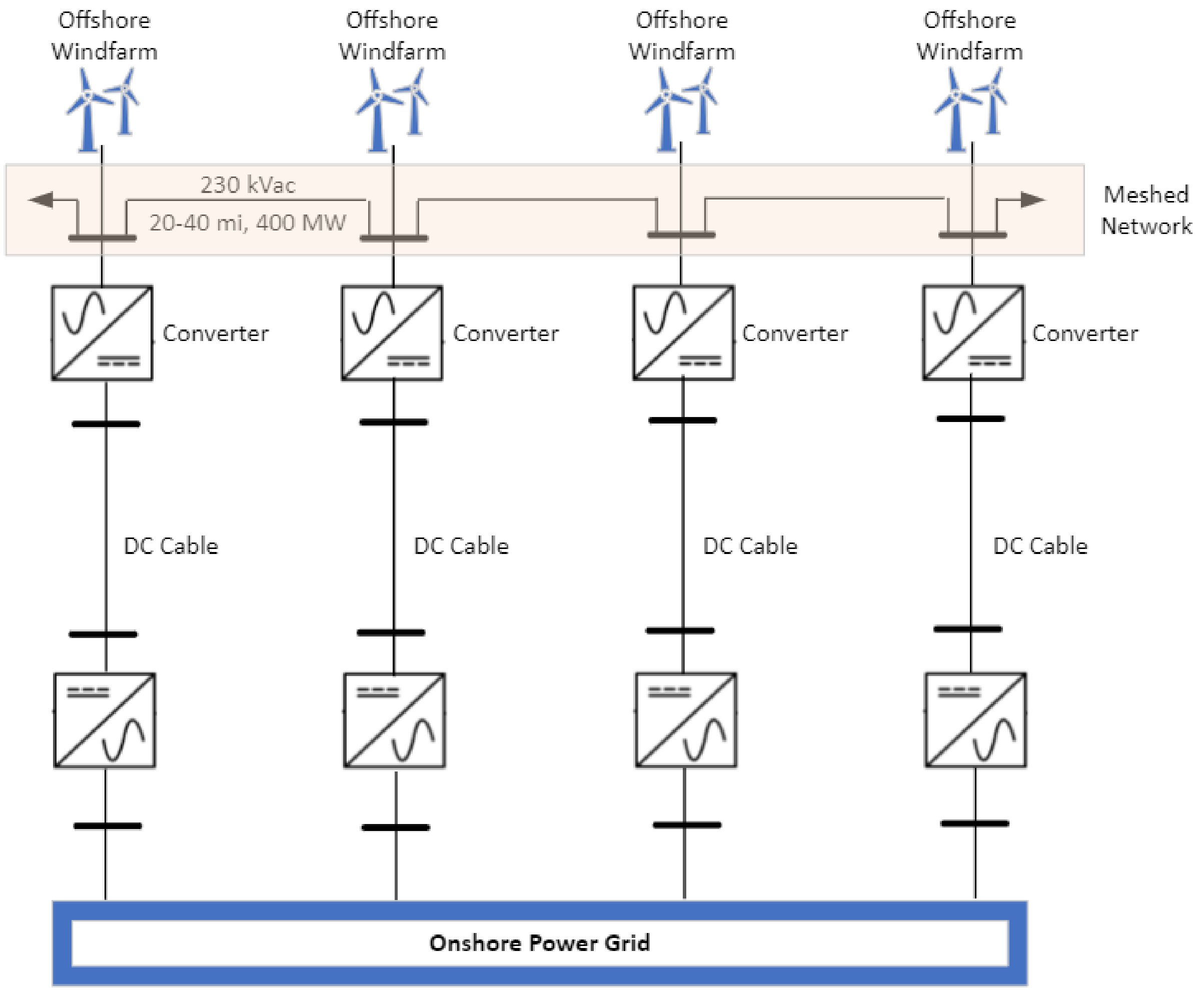
3 Meshed Offshore Wind Transmission System

The NYSERDA Meshed-Ready Technical Requirements guided development of the meshed offshore transmission configuration and represents an illustrative configuration. Bidders in the most recent and future NYSERDA procurements offering radial connections include bids with offshore transmission platforms that can accommodate the interconnections and substation configurations necessary to create the meshed network. Through this alternative, new OSW facilities could be constructed to facilitate integrating the radial lines into a meshed system later, if necessary. This design is referred to as meshed-ready.

Figure 4 presents the meshed-ready design, as adopted from NYSERDA's Meshed-Ready Technical Requirements referenced earlier. The study used the following assumptions that define the parameters that allow the system to be considered meshed-ready:

1. Meshed-ready projects are designed to integrate into the system as Figure 4 demonstrates.
2. The radial connections from the offshore substation to the injection point will be based on voltage source converter (VSC) HVDC technology:
    - The meshed network will not include projects with alternating current (AC) radial interconnection.
    - Each project will have a dedicated radial HVDC link that will transmit power to the shore.
3. The radial HVDC link can transfer the rated capacity of the wind power generated by the corresponding OSW generation facility regardless of its connection to the meshed network.
4. Implementing a meshed network will not increase the total capacity of the offshore grid.
5. Each meshed-ready offshore substation will include two AC connections, each able to transmit at least 400 MW of power throughout the meshed network as defined by meshed transfer capacity.
6. The distance between two meshed OSW substations is limited to 40 miles to support connections.
7. The meshed network is designed at a voltage level of 230 kV.
8. The offshore grid is designed for unidirectional flows from the OSW substations to the onshore POIs.

Figure 4. Meshed-Ready Offshore Design



The principles documented earlier were used to guide the development of an offshore meshed grid configuration. The WEAs were paired to one another based on distance guidelines and opportunities to create a diverse mix of POIs distributed between intrazonal, interzonal, and interregional connections.

Figure 5. Meshed-Ready Design for Pathway 1, Year 2050

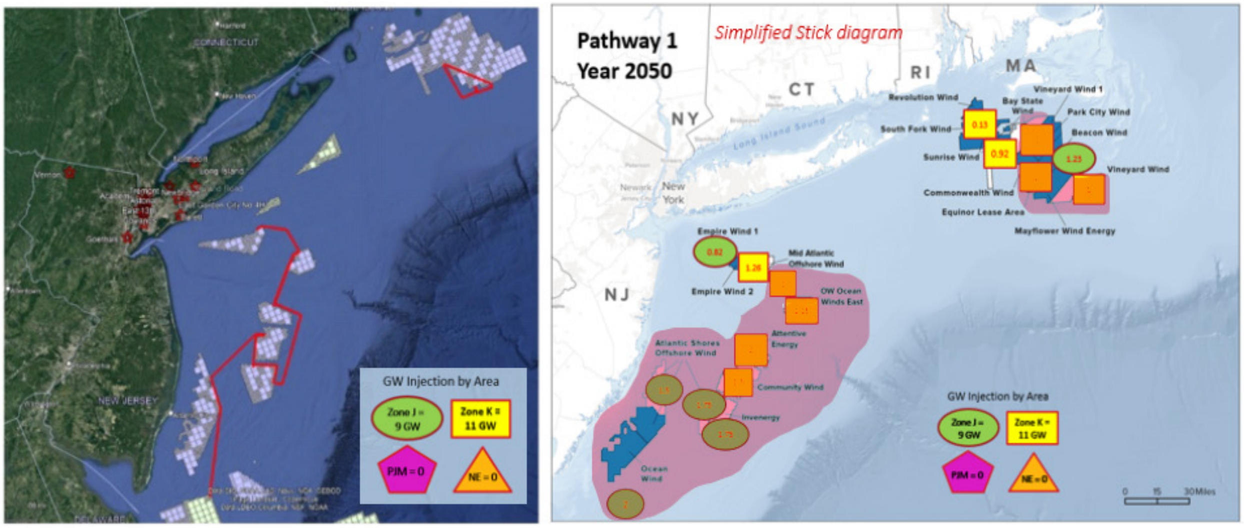


Figure 5 presents a meshed-ready design for Pathway 1, Year 2050. Importantly, the configurations under study took a phased approach from 2035 to 2050, which incrementally transitioned from intrazonal, interzonal, and interregional meshed system designs. The meshed design also favored selection of 320 kV designs in earlier years (2035) toward 525 kV designs in future years (2040/2050).

The pathways were developed using information available at the time of study commencement in November 2022. This reflected a mix of confirmed contracts, designated lease areas, lease areas currently under negotiation, and specified POIs as they stood at that time.

4 Model Development and Benefits Analysis

As stated in section 2, power flow and economic planning models were developed to support the overall analysis. Power flow modeling and analysis was performed using Siemens PSS/E and PowerGem TARA software, while economic models were developed using Hitachi GridView software tools. The project team developed models that reflect three years (2035, 2040, and 2050) across each of the three pathways for a comprehensive benefit/cost analysis.

The portfolio of generation and storage resources and load forecasts from CAC Draft Scoping Plan, Scenario 3,[13] were disseminated down to nodal representation in the power flow and economic planning models. This process was iteratively achieved through balancing capacity additions against retirements, considering new load additions and security analysis. The portfolio mix reflected all neighboring regions achieving their current state goals. The economic planning models were baselined against the CAC Draft Scoping Plan, Scenario 3, before initiating further analysis. The primary benchmarking metrics included annual gigawatt-hours (GWh) generation, interface flows, and net-zero interregional energy exchange.

The power flow models were used to disseminate the zonal portfolio of resources down to the nodal level through multiple iterations of security-constrained headroom analysis. Power flow analysis was used to identify prospective OSW POIs, develop illustrative transmission expansion portfolios, evaluate the impact of extreme events, and develop preliminary OSW connection conceptual designs.

The economic planning models were developed using the base power flow models. They were used to calculate the overall benefits of meshed design configurations. The economic models include a nodal representation of the eastern interconnection and model the pathway consistent with findings from the power flow studies (i.e., OSW POIs and transmission expansion portfolios).

Importantly, each of the pathways was evaluated under radial and meshed configurations. Salient features remain consistent between the two configurations, including generation portfolio, load forecasts, POIs, illustrative onshore transmission expansion, and distribution of OSW between NYCA and neighbors. The only difference is the offshore connection concept—radial versus meshed—which allows for an adequate comparison in key benefit metrics and quantification of overall benefits from meshed grids.

4.1 Benefits under Evaluation

The project team screened a range of benefit categories that could support a quantitative assessment of benefits from meshed offshore grids. To quantify the benefits, simulations were performed for 2035, 2040, and 2050. Linear interpolation was used between these periods, and the periods beyond 2050 assume the same benefits from 2050 carry forward.

The following three benefit categories were selected:

1. **Adjusted production cost (APC) savings:** The APC has been calculated consistent with the NYISO's System and Resource Outlook procedures. This quantity represents the cost of generation to serve load and reserve requirements, adjusted for cost from imports/exports. This benefit category has been directly calculated from the production-cost simulation results.
2. **Increased availability:** Monte Carlo–based simulations assessed the volume of avoided curtailments due to the increased availability of OSW during offshore grid events. The offshore grid events include scheduled and forced outages of offshore grid infrastructure (due to maintenance, equipment failure, or catastrophic events, e.g., ship anchor drag). The avoided curtailments are monetized using location based marginal prices (LBMPs) in Zone J and Zone K from the production-cost simulations. This benefit category has been calculated using a combination of spreadsheet analysis and prices from the production-cost simulations.
3. **Avoided onshore transmission costs:** This benefit has been quantified as the reduction in investment needed in the illustrative onshore transmission upgrades. The offshore grid infrastructure creates an alternative path for OSW to directly reach the load centers, reducing the stress on existing onshore infrastructure. In particular, the study indicates that meshed infrastructure may reduce the number of onshore cables needed between Zone K and the rest of the State. This benefit category has been directly calculated from the production simulation results by monitoring the use of the offshore meshed grid relative to the interzonal ties. The increased use of the offshore meshed transmission system reduces the need for onshore cables or reinforcements compared to the initial pathway setup described in section 2.

Each benefit category was evaluated as unique and distinct to avoid overestimation (double counting) of benefits. Additionally, the benefits were monetized for qualitative assessment. The benefits across these three categories are calculated as the delta between radial and meshed configurations.

4.2 Adjusted Production-Cost Savings

The adjusted production costs accounted for 71% to 85% of the total benefits observed across the three pathways, reflecting a net present value (NPV) calculated for the asset's lifespan from 2035 to 2080. Within this analysis, several key observations were made, particularly for 2050.

First, curtailments saw a reduction ranging from 300 GWh, marking a 9% decrease, to 2,690 GWh, which represented a 50% reduction across the pathways. The significant decrease in curtailments contributes to production-cost savings estimated between $242 million and $584 million. See appendix B, Table B-1, for detailed information.

Furthermore, reducing curtailments minimized the reliance on higher-cost emission-free resources within New York State, showcasing economic and environmental benefits. Additionally, the analysis identified increased energy flows into Zone J from Zone K, which the meshed infrastructure facilitated. This strategic use of meshed connections allowed for redirecting OSW energy toward higher-priced regions whenever possible, enhancing economic efficiency and maximizing the benefits of the meshed system design. See Appendix C for a summary of the production-cost modeling results.

4.3 Increased Availability

The analysis highlighted that the increased availability metric contributed between 7% and 14% of the total benefits observed across the three pathways, encapsulating a NPV for the asset's lifetime from 2035 to 2080. This increase in availability led to notable observations for 2050.

First, the avoidance of curtailments, when compared to a radial design, resulted in savings ranging from $42 million to $53 million in 2050. This financial benefit was attributed to approximately 170 GWh to 190 GWh of curtailment being avoided due to offshore grid events. These events included planned and unplanned maintenance activities and extreme situations such as ship anchor drag. The stochastic analysis considered forced and unforced outage rates derived from historical information[14] and data collected from the project team (vendors). See appendix B, Table B-2, for detailed information.

Furthermore, under the radial design, typical offshore grid events that involve an outage of critical components (converter stations or cables) would have resulted in a complete loss of OSW production. This contrast highlighted the resilience and economic advantages the meshed grids provide in mitigating the impacts of offshore grid events on wind production.

4.4 Avoided Onshore Transmission Costs

The avoided onshore transmission costs metric was found to account for 9% to 15% of the benefits across the three pathways, reflecting a NPV for the asset's lifetime from 2035 to 2080. Observations for 2050 revealed that, across these pathways, the metric identified the avoidance of one additional cable between Zone K and the rest of the State, which translated to approximately $500 million in avoided investments. This considerable saving in investment costs could be directly attributed to the increased use of the offshore meshed grid, which supported the efficient delivery of OSW energy directly into Zone J.

5 The Cost of Building Meshed Networks

Section 4 of the report describes key differences between radial and meshed transmission system designs for each pathway. The study then developed cost information to compare both designs. Meshed systems include the costs of a radial system, meshed-ready infrastructure, and meshed implementation (i.e., meshing cables). The delta in cost between a truly radial and meshed system is the cost associated with meshed-ready infrastructure and meshed implementation.

In developing cost information, the study assumed the following equipment, outlined in the NYSERDA Meshed-Ready Technical Requirements, would be required for meshed systems:

- AC system architecture was based on 400 MW blocks, 2 x 420 megavolt ampere (MVA) for 800 MW system.
- For 800 MW system, we include 66/275kV, 2 x 450 MVA main power transformers.
- To ensure trouble-free operations, power quality for offshore platform is managed through 2 x 200 MVAr (megavolt ampere [reactive]) shunt reactors (variable type*, i.e.,* load tap changer [LTC]); size of reactors may vary depending on cable length.
- For the offshore 275 kV switchyard, we use 2 x 300 kV, 4,000 A (ampere), gas-insulated switchgear (GIS) plus gas-insulated bus for transformer and cable pothead connections.
- Offshore substation protection and controls (P&C), supervisory control and data acquisition (SCADA), and communication systems are included.
- Includes structural steel members and components for equipment supports, fire barriers, and oil containment.
- Platform jacket for the offshore 275 kV AC substation infrastructure.

The radial system cost estimates developed for this analysis do not include these costs because they are premised on a truly radial design without considering future expansion capability into an offshore meshed transmission network.

The overall cost of meshed-ready infrastructure was estimated to be $99 millon per WEA. The cost of meshing cables is approximately $4.5 million per mile (assuming cable lengths in the 20–40-mile range). In addition to the capital investment cost, O&M costs were estimated as part of the annual operation and maintenance budget to be 1% of the capital costs. The assets have a 30-year investment life, and the analysis assumes replacements until the end of life of the last investment (installed in 2050). All cost estimates were derived from vendor information.

The costs were compared to previous NYSERDA estimates as part of a baselining exercise.[15] The overall costs were found to be higher due to adjustments for inflation, differences in commodity price accounting for global trends, risk and warranty, sales and admin, and the cost of the platform jacket. Additionally, prior cost estimates were based on the 300 MW interlink capability of the meshing cables, which has been updated to 400 MW, per recent guidance.

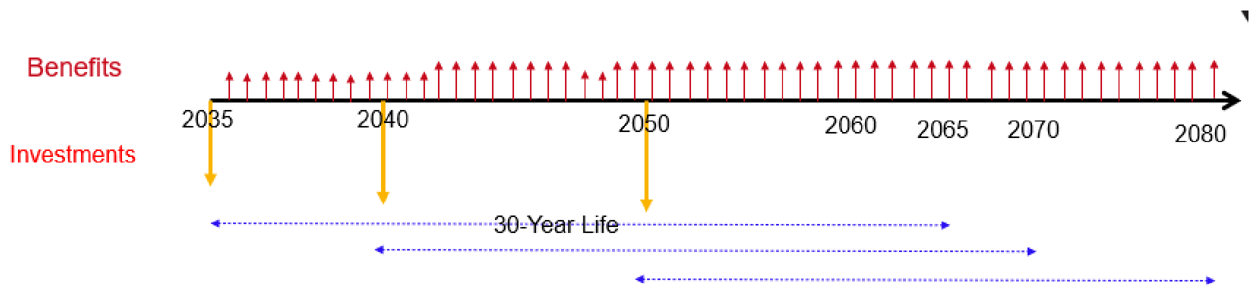
Across the three pathways, the total investment costs were estimated based on the WEAs under consideration and the meshing cables between WEAs. The total overnight capital costs vary from $2.5 billion to $2.6 billion. Appendix A presents the levelized costs across each pathway.

6 Benefit/Cost Analysis

Benefit/cost analysis was performed to measure the benefits of a meshed grid, relative to the incremental investment. Discussions with DPS staff on the benefit categories, cost categories, and lifetime of asset investments guided the overall framework. While comparing the cost and benefits of an asset with a longer life, the comparison is typically conducted over the useful life of the asset. In the case of offshore grid investments, these are typically 30 years.

To support the evaluation, a levelized real cost approach has been used to cover the investment horizon through 2080, which includes replacement of assets every 30 years and O&M costs estimated at 1% of the Capex.[16] The O&M costs were estimated from vendor-supplied data using historical and expected trends; the concept is illustrated in Figure 6. The benefits were extended across the asset's lifetime by carrying out the 2050 benefits until 2080. The analysis assumes a real discount rate of 4.78%.[17]

Figure 6. Levelized Costs



The overall benefit/cost ratios are calculated as the NPV of benefits through 2080 divided by NPV of levelized costs incurred until 2080. Key findings across all the pathways indicate the benefit/cost ratios greater than 1.5 and are presented below in further detail for each pathway. Appendix A has details on the benefits through time.

6.1 Pathway 1

Pathway 1 represents a New York State–only meshed configuration with a combination of interzonal and intrazonal meshing between Zones J and K.

The study results indicated a benefit/cost ratio of 1.7 for Pathway 1. Additionally, a benefit/cost ratio of greater than 1 was achieved by 2043, indicating that the annualized benefits exceed the annualized investment costs within eight years. The reduction in curtailment led to a decrease in the need for high-cost emission-free generation within New York State[18] because no significant changes occurred in imports. Additionally, increased energy flowed into Zone J through the meshed grid, which facilitated the movement of OSW-generated electricity from lower-cost regions to higher-cost regions. See appendix C for additional results from the production-cost model.

In 2035, limited benefits were observed due to meshed transmission opportunities being limited to intrazonal (i.e., no meshing between Zone J and Zone K OSW project). This is demonstrated by the negative net benefits observed in Table 2 for 2035. In 2040, an increase in overall benefits was observable following interzonal meshed implementation. Table 2 provides a breakdown of the benefits, levelized total costs, and net benefits for each study year—2035, 2040, and 2050. Table 3 presents the NVP of benefits and costs across the horizon from 2035 to 2080.

Table 2. Annual Benefits and Costs of Pathway 1

All in 2020 Dollars	2035	2040	2050
Benefits ($M)	5	158	326
Levelized Total Costs ($M)	50	107	186
Net Benefits ($M)	-45	51	141

Table 3. Net Present Value of Benefits and Costs of Pathway 1 across the Project Lifetime

All in 2020 Dollars	
NPV of Benefits ($M)	3,928
NPV of Levelized Total Costs ($M)	2,333
Benefit/Cost Ratio	1.7

6.2 Pathway 2

Pathway 2 represents an interregional meshed configuration with a meshed design that leverages PJM connections.

The study results indicated a benefit/cost ratio of 3.2 for Pathway 2. Additionally, a benefit/cost ratio of greater than 1 was achieved by 2041, indicating that the annualized benefits exceed the annualized investment costs within six years. The reduction in curtailment from the meshed grid resulted in a corresponding decline in the generation from high-cost emission-free resources within New York State. Compared to the interplay of increased OSW generation and adjustments in emission-free generation, the overall fluctuations in imports/exports remained quite minimal. Nevertheless, even with these modest net changes in the import/export dynamic between New York State and its neighboring areas, the shifts in the timing and distribution of energy flows were substantial enough to enhance the efficiency of the system's dispatch.

In 2035, limited benefits were observed due to meshed transmission opportunities being limited to intrazonal (i.e., no meshing between Zone J and Zone K OSW project). Table 4 shows the negative net benefits for 2035. In 2040, an increase in overall benefits was observable following interzonal (New York State–only) and interregional (PJM) meshed implementation.

Table 4 provides a breakdown of the benefits, levelized total costs, and net benefits for each study year—2035, 2040, and 2050. Table 5 presents the NPV of benefits and costs across the horizon from 2035 to 2080.

Table 4. Annual Benefits and Costs of Pathway 2

All in 2020 Dollars	2035	2040	2050
Benefits ($M)	7	274	657
Levelized Total Costs ($M)	43	92	168
Net Benefits ($M)	-44	167	462

Table 5. Net Present Value of Benefits and Costs of Pathway 2 across the Project Lifetime

All in 2020 Dollars	
NPV of Benefits ($M)	7.638
NPV of Levelized Total Costs ($M)	2,406
Benefit/Cost Ratio	3.2

6.3 Pathway 3

Pathway 3 represents an interregional meshed configuration with a meshed design that leverages connections to neighbors (i.e., PJM and ISO-NE).

The study results indicated a benefit/cost ratio of 2.9 for Pathway 3. Additionally, a benefit/cost ratio of greater than 1 was achieved by 2041, indicating that the annualized benefits exceed the annualized investment costs within six years. The overall impacts on curtailment were minor because the total volume of curtailment was initially small. This is attributed to the selected location of POIs and the distribution of OSW capacity between Zone J, Zone K, and neighbors. Pathway 3 facilitated an increase in net imports of lower-cost generation from ISO-NE through the combination of onshore transmission expansion and the offshore mesh grid, which acted to displace the higher-cost thermal generation in Zones J and K. This adjustment in both the time and location of energy flows contributed to the improvement of overall system dispatch, enhancing the operational efficiency of the grid.

In 2035, limited benefits were observed due to meshed transmission opportunities being limited to intrazonal (i.e., no meshing between Zone J and Zone K OSW project). In 2040, an increase in overall benefits were observable following interzonal (New York State only) and interregional (PJM and ISO-NE) meshed implementation.

Table 6 provides a breakdown of the benefits, levelized total costs, and net benefits for each study year—2035, 2040, and 2050. Table 7 presents the NPV of benefits and costs across the horizon from 2035 to 2080.

Table 6. Annual Benefits and Costs of Pathway 3

All in 2020 Dollars	2035	2040	2050
Benefits ($M)	7	256	571
Levelized Total Costs ($M)	50	107	191
Net Benefits ($M)	-44	149	380

Table 7. Net Present Value of Benefits and Costs of Pathway 3 across the Project Lifetime

All in 2020 Dollars	
NPV of Benefits ($M)	6,821
NPV of Levelized Total Costs ($M)	2,377
Net Benefits ($M)	2.9

As mentioned in section 2, a scenario was also evaluated where only the current State goal of 9 GW of OSW by 2035 is deployed and sustained in 2040 and 2050. This scenario also had net benefits greater than 1.5. See appendix D for additional information about this scenario.

7 Findings and Recommendations

The analysis explored three OSW expansion pathways that offer a mix of regional meshed connections and potential interregional networked transmission connections to achieve 20 GW of OSW capacity in New York State. Despite the recognizable differences across the pathways, the study observed several trends that support the findings discussed below:

- **Benefit/cost ratios:** The analysis found that, across all the pathways, meshed configurations yielded benefit/cost ratios greater than 1.5. This outcome indicates that the combination of benefits from these configurations exceeds the costs of the incremental investments required. Among the three benefit categories identified, production-cost savings emerged as the largest, accounting for 71% to 85% of the overall benefits across all pathways, due to improved efficiencies in market economics and dispatch.
- **Interzonal versus intrazonal mesh:** The study revealed that the value of meshing was most evident when opportunities for interzonal (e.g., Zone J to Zone K) or interregional (e.g., Zone J/K to PJM/ISO-NE) connections existed. Conversely, the analysis identified limited benefits from meshing when it was restricted to intrazonal (e.g., Zone J to Zone J or Zone K to Zone K). The value of zonal diversity significantly influenced the overall benefits and the benefit/cost ratios.
- **Reduced curtailment risk due to onshore and offshore grid events:** Designs featuring meshed systems were observed to contribute to a reduction of 9% to 50% in OSW curtailment. This reduction in curtailment was attributed to the maximized utilization of meshed grids and the available headroom on HVDC connections to onshore POIs during both onshore and offshore grid events.
- **Reduced onshore transmission investments:** Maximizing the utilization of the offshore meshed grids saw a noted reduction in the reliance on onshore upgrades between Zone K and the rest of the State. The avoidance of new infrastructure costs resulted in $500 million savings for the benefit of ratepayers.

While the findings from the study identified multiple benefits to a meshed OSW transmission system, further research and analysis to comprehensively address technical, regulatory, and market design challenges will be required to fully realize those benefits. Key actions associated with addressing these challenges would result in incremental costs to fully realize the projected benefits, as well as potential additional benefits not quantified by this study.

Key areas for future research that might be addressed through a combination of NYISO projects, inter-ISO, interstate collaboratives, and/or the U.S. Department of Energy (DOE) and the Federal Energy Regulatory Commission (FERC) projects:

- **Intraregional market and operations issues**
  Intraregional market and operations issues are becoming increasingly complex with OSW capacity and meshed systems integration. For example, complexities arise from the implications to energy, ancillary service, and capacity markets when OSW generators can be dispatched to different zones. There could be a need for broader market and operation system improvements to allow seamless interaction and control between meshed offshore transmission systems and the onshore transmission grid. Additionally, the potential for bidirectional flow across HVDC tie-lines presents opportunities for higher benefits with additional market and operational challenges that would need to be addressed. Future NYISO projects may tackle these challenges, aiming to enhance the reliability and efficiency of intraregional electricity markets and operations. Costs associated with market and operational system improvements identified by any such projects would need to be considered.
- **Interregional market and operations issues**
  Interregional market and operations issues involve the accommodation of energy exchange and essential grid services across regions, which includes balancing imbalances between regions and offering ancillary service market products. However, jurisdictional challenges are prominent with regard to interregional offshore grid operations. The capacity for interregional transfer also impacts individual state offshore renewable energy credit (OREC) contracts, and the utilization of individual generator tie-lines as part of an offshore transmission network raises several implications. To address these complex issues, future efforts may involve cross-state and interstate collaborative projects or DOE- and FERC-led initiatives.
- **Network-ready equipment standardization and HVDC technical issues**
  Regarding HVDC technical issues, specific requirements would need to be met to ensure multivendor interoperability. Developing HVDC technical standards and establishing common meshed-ready design standards for use across state OSW solicitations are crucial to realize interregional benefits. These technical considerations are being addressed through interstate collaborative efforts and standardization DOE-supported work.
- **Reliability criteria**
  The development of reliability standards that are specific to meshed offshore transmission systems is necessary for planning and deploying those systems. There would need to be updates to the existing ISO maximum single infeed limits, which refers to the single largest loss of source/generation contingency a system can handle, as well as revisions or a reexamination of how contingencies are considered for bipole HVDC systems.
- **Other regulatory issues**
  Implementing an interregional meshed offshore transmission system would introduce interregional cost allocation and recovery challenges. To advance the meshed network configurations, a transparent and efficient procedure for determining cost allocation and associated cost recovery mechanism will be necessary. Future projects by cross-ISO entities, interstate collaborations, and/or DOE/FERC initiatives may provide solutions to these challenges, ultimately leading to more reliable and efficient power transmission infrastructures.

8 References

New York State Climate Action Council. 2021. “New York State Climate Action Council Draft Scoping Plan.” https://climate.ny.gov/Resources/Draft-Scoping-Plan

New York State Energy Research and Development Authority (NYSERDA). 2022. “Offshore Wind Solicitation ORECRFP22-1 – Appendix G - Meshed Ready Technical Requirements.” https://portal.nyserda.ny.gov/CORE_Solicitation_Document_Page?documentId=a0l8z000000Gzo4&_gl=1*9wg79h*_gcl_au*MTIwOTMzMjgyNS4xNzE1MTAyNDM3*_ga*MTAzOTA5MTI4MS4xNjkwNTY3MjYz*_ga_DRYJB34TXH*MTcxODYzNjQ4MC41MC4xLjE3MTg2MzY3MzMuMzIuMC4w

New York State Energy Research and Development Authority (NYSERDA). 2023. “Offshore Wind Cable Corridor Constraints Assessment.” Report Number 23-06. Prepared by WSP USA, New York, NY and VHB, New York, NY. https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Programs/Offshore-Wind/2306-Offshore-Wind-Cable-Corridor-Constraints-Assessment--completeacc.pdf

Conseil International des Grands Réseaux Electriques (CIGRE), Survey of the Reliability of HVDC Systems throughout World during 2019–2020. (2022) Reference: B4-11135_2022. https://www.e-cigre.org/publications/detail/b4-11135-2022-survey-of-the-reliability-of-hvdc-systems-throughout-world-during-2019-2020.html

Appendix A. Breakdown of Benefit/Cost Categories

A.1 Pathway 1

Table A-1. Pathway 1 Breakdown of Benefit/Cost Categories

All in 2020 Dollars	
NPV of Benefits ($M)	3,928
NPV of Levelized Total Costs ($M)	2,333
Benefit/Cost Ratio	1.7

All in 2020 Dollars	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Production-Cost Benefits ($M)	0	0	0	0	0	137	148	158	169	179	190
Avoided Curtailment (Availability)($M)	5	9	12	15	18	21	24	27	31	34	37
Avoided Transmission—Levelized Cost ($M)	0	0	0	0	0	0	0	0	0	0	0
Total Benefits ($M)	5	9	12	15	18	158	172	185	199	213	226
Levelized Investment Costs (including O&M)	50	50	50	50	50	107	107	107	107	107	107
Total Benefits—Levelized Investment Costs	-45	-42	-38	-35	-32	51	65	79	92	106	120
All in 2020 Dollars	**2046**	**2047**	**2048**	**2049**	**2050**	**2051**	**2052**	**2053**	**2054**	**2055**	**2056**
Production Cost Benefits ($M)	200	211	221	232	242	242	242	242	242	242	242
Avoided Curtailment (Availability)($M)	40	43	46	50	53	53	53	53	53	53	53
Avoided Transmission—Levelized Cost ($M)	0	0	0	0	32	32	32	32	32	32	32
Total Benefits ($M)	240	254	267	281	326	326	326	326	326	326	326
Levelized Investment Costs (including O&M)	107	107	107	107	186	186	186	186	186	186	186
Total Benefits–Levelized Investment Costs	133	147	160	174	141	141	141	141	141	141	141

Table A-1 (continued)

All in 2020 Dollars	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	
Production Cost Benefits ($M)	242	242	242	242	242	242	242	242	242	242	242	
Avoided Curtailment (Availability)($M)	53	53	53	53	53	53	53	53	53	53	53	
Avoided Transmission—Levelized Cost ($M)	32	32	32	32	32	32	32	32	32	32	32	
Total Benefits ($M)	326	326	326	326	326	326	326	326	326	326	326	
Levelized Investment Costs (including O&M)	186	186	186	186	186	186	186	186	186	186	186	
Total Benefits—Levelized Investment Costs	141	141	141	141	141	141	141	141	141	141	141	
All in 2020 Dollars	**2068**	**2069**	**2070**	**2071**	**2072**	**2073**	**2074**	**2075**	**2076**	**2077**	**2078**	**2079**
Production Cost Benefits ($M)	242	242	242	242	242	242	242	242	242	242	242	242
Avoided Curtailment (Availability)($M)	53	53	53	53	53	53	53	53	53	53	53	53
Avoided Transmission—Levelized Cost ($M)	32	32	32	32	32	32	32	32	32	32	32	32
Total Benefits ($M)	326	326	326	326	326	326	326	326	326	326	326	326
Levelized Investment Costs (including O&M)	186	186	186	186	186	186	186	186	186	186	186	186
Total Benefits–Levelized Investment Costs	141	141	141	141	141	141	141	141	141	141	141	141

A.2 Pathway 2

Table A-2. Pathway 2 Breakdown of Benefit/Cost Categories

All in 2020 Dollars	
NPV of Benefits ($M)	7.638
NPV of Levelized Total Costs ($M)	2,406
Benefit/Cost Ratio	3.2

All in 2020 Dollars	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Production-Cost Benefits ($M)	0	0	0	0	0	217	254	290	327	364	400
Avoided Curtailment (Availability)($M)	7	9	11	14	16	18	21	23	25	28	30
Avoided Transmission—Levelized Cost ($M)	0	0	0	0	0	0	0	0	0	0	0
Total Benefits ($M)	7	9	11	14	16	235	274	313	352	391	430
Levelized Investment Costs (including O&M)	50	50	50	50	50	107	107	107	107	107	107
Total Benefits—Levelized Investment Costs	-44	-41	-39	-37	-34	128	167	206	245	284	324
All in 2020 Dollars	**2046**	**2047**	**2048**	**2049**	**2050**	**2051**	**2052**	**2053**	**2054**	**2055**	**2056**
Production-Cost Benefits ($M)	437	474	510	547	584	584	584	584	584	584	584
Avoided Curtailment (Availability)($M)	32	35	37	39	42	42	42	42	42	42	42
Avoided Transmission—Levelized Cost ($M)	0	0	0	0	32	32	32	32	32	32	32
Total Benefits ($M)	469	508	547	586	657	657	657	657	657	657	657
Levelized Investment Costs (including O&M)	107	107	107	107	195	195	195	195	195	195	195
Total Benefits—Levelized Investment Costs	363	402	441	480	462	462	462	462	462	462	462

Table A-2 (continued)

All in 2020 Dollars	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	
Production-Cost Benefits ($M)	584	584	584	584	584	584	584	584	584	584	584	
Avoided Curtailment (Availability)($M)	42	42	42	42	42	42	42	42	42	42	42	
Avoided Transmission—Levelized Cost ($M)	32	32	32	32	32	32	32	32	32	32	32	
Total Benefits ($M)	657	657	657	657	657	657	657	657	657	657	657	
Levelized Investment Costs (including O&M)	195	195	195	195	195	195	195	195	195	195	195	
Total Benefits—Levelized Investment Costs	462	462	462	462	462	462	462	462	462	462	462	
All in 2020 Dollars	**2068**	**2069**	**2070**	**2071**	**2072**	**2073**	**2074**	**2075**	**2076**	**2077**	**2078**	**2079**
Production-Cost Benefits ($M)	584	584	584	584	584	584	584	584	584	584	584	584
Avoided Curtailment (Availability)($M)	42	42	42	42	42	42	42	42	42	42	42	42
Avoided Transmission—Levelized Cost ($M)	32	32	32	32	32	32	32	32	32	32	32	32
Total Benefits ($M)	657	657	657	657	657	657	657	657	657	657	657	657
Levelized Investment Costs (including O&M)	195	195	195	195	195	195	195	195	195	195	195	195
Total Benefits—Levelized Investment Costs	462	462	462	462	462	462	462	462	462	462	462	462

A.3 Pathway 3

Table A-3. Pathway 3 Breakdown of Benefit/Cost Categories

All in 2020 Dollars	
NPV of Benefits ($M)	6,821
NPV of Levelized Total Costs ($M)	2,377
Net Benefits ($M)	2.9

All in 2020 Dollars	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Production-Cost Benefits ($M)	0	0	0	0	0	236	262	288	313	339	365
Avoided Curtailment (Availability)($M)	7	9	12	14	17	20	22	25	27	30	33
Avoided Transmission—Levelized Cost ($M)	0	0	0	0	0	0	0	0	0	0	0
Total Benefits ($M)	7	9	12	14	17	256	284	312	341	369	398
Levelized Investment Costs (including O&M)	50	50	50	50	50	107	107	107	107	107	107
Total Benefits—Levelized Investment Costs	-44	-41	-38	-36	-33	149	177	205	234	262	291
All in 2020 Dollars	**2046**	**2047**	**2048**	**2049**	**2050**	**2051**	**2052**	**2053**	**2054**	**2055**	**2056**
Production-Cost Benefits ($M)	391	416	442	468	494	494	494	494	494	494	494
Avoided Curtailment (Availability)($M)	35	38	40	43	46	46	46	46	46	46	46
Avoided Transmission—Levelized Cost ($M)	0	0	0	0	32	32	32	32	32	32	32
Total Benefits ($M)	426	454	483	511	571	571	571	571	571	571	571
Levelized Investment Costs (including O&M)	107	107	107	107	191	191	191	191	191	191	191
Total Benefits–Levelized Investment Costs	319	347	376	404	380	380	380	380	380	380	380

Table A-3 (continued)

All in 2020 Dollars	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	
Production-Cost Benefits ($M)	494	494	494	494	494	494	494	494	494	494	494	
Avoided Curtailment (Availability)($M)	46	46	46	46	46	46	46	46	46	46	46	
Avoided Transmission—Levelized Cost ($M)	32	32	32	32	32	32	32	32	32	32	32	
Total Benefits ($M)	571	571	571	571	571	571	571	571	571	571	571	
Levelized Investment Costs (including O&M)	191	191	191	191	191	191	191	191	191	191	191	
Total Benefits—Levelized Investment Costs	380	380	380	380	380	380	380	380	380	380	380	
All in 2020 Dollars	**2068**	**2069**	**2070**	**2071**	**2072**	**2073**	**2074**	**2075**	**2076**	**2077**	**2078**	**2079**
Production-Cost Benefits ($M)	494	494	494	494	494	494	494	494	494	494	494	494
Avoided Curtailment (Availability)($M)	46	46	46	46	46	46	46	46	46	46	46	46
Avoided Transmission—Levelized Cost ($M)	32	32	32	32	32	32	32	32	32	32	32	32
Total Benefits ($M)	571	571	571	571	571	571	571	571	571	571	571	571
Levelized Investment Costs (including O&M)	191	191	191	191	191	191	191	191	191	191	191	191
Total Benefits—Levelized Investment Costs	380	380	380	380	380	380	380	380	380	380	380	380

Appendix B. Curtailment Summary

Curtailment reductions are presented in Table B-1 and Table B-2 for all three Pathways.

Table B-1. Avoided Curtailment Due to More Efficient Economic Dispatch

Year 2050, 20 GW OSW	Pathway 1		Pathway 2		Pathway 3	
Configuration	Radial	Mesh	Radial	Mesh	Radial	Mesh
Total OSW Generation (GWh)	79,432	80,795	81,748	84,436	82,262	82,562
Total OSW Curtailment (GWh)	6,611	5,248	5,328	2,638	3271	2971
OSW Curtailment Percentage (%)	7.7%	6.1%	6.1%	3.0%	3.8%	3.5%
Curtailment Reduction under Meshed Configuration (GWh)		1,363		2,690		300
OSW Curtailment Reduction Percentage		20.6%		50.5%		9.2%

Table B-2. Avoided Curtailment Due to Increased Availability

Year 2050	Pathway 1	Pathway 2	Pathway 3
OSW Curtailment under Radial Configuration (GWh)	610	635	596
OSW Curtailment under Mesh Configuration (GWh)	171	188	173
OSW Curtailment Reduction Percentage	72%	70%	71%

Appendix C. Other Statistics for All Pathways

Table C-1. Generation Capacity by Category for All 20 GW Offshore Wind Pathways

Fuel Mix (Capacity)	Unit	2035	2040	2050
Nuclear	MW	3,355	3,355	2,135
Thermal	MW	19,781	23,522	25,359
Hydro	MW	4,613	4,613	4,613
UPV	MW	28,625	41,420	60,604
BTM-PV	MW	12,788	15,764	15,764
LBW	MW	10,668	12,523	16,747
OSW	MW	9,000	15,000	20,000

Table C-2. Generation/Imports (gigawatt-hours) by Category - Pathway 1

	2035		2040		2050	
GWh	Radial	Mesh	Radial	Mesh	Radial	Mesh
Nuclear	26,496	26,496	26,496	26,496	16,727	16,727
Hydro	27,485	27,502	25,896	25,912	25,445	25,424
Thermal	35,600	35,723	12,007	11,667	23,733	22,704
Solar	41,205	41,303	59,830	59,977	77,280	77,348
LBW	37,096	37,085	42,356	42,337	52,851	52,750
OSW	38,382	38,199	61,999	62,354	79,432	80,794
Net imports from HQ	16,839	16,834	18,832	18,838	18,198	18,279
Net imports from PJM, ISO-NE, and IESO	-5,337	-6,505	2,678	3,053	3,506	3,423
Net energy for load	196,255	196,255	227,001	227,001	269,821	269,821

Table C-3. Generation/Imports (gigawatt-hours) by Category - Pathway 2

GWh	2035		2040		2050	
	Radial	Mesh	Radial	Mesh	Radial	Mesh
Nuclear	26,496	26,496	26,496	26,496	16,727	16,727
Hydro	27,471	27,504	25,927	25,964	25,503	25,503
Thermal	35,782	35,822	12,379	11,235	25,876	23,206
Solar	41,213	41,300	60,168	60,539	78,223	78,696
LBW	37,086	37,099	42,405	42,445	53,230	53,263
OSW	38,035	38,073	58,216	58,684	67,073	69,955
Net imports from HQ	16,844	16,839	19,149	19,132	19,157	18,970
OSW generation in PJM/NE			4194	4157	14,674	14,482
Net imports from PJM, ISO-NE, IESO, before accounting for NYS-procured OSW injections in those regions	-5,058	-6,226	5,117	5,460	10,733	10,781
NYS-procured OSW in PJM and ISO-NE*	0	0	4,194	4,157	14,674	14,482
Net Imports from PJM and ISO-NE after accounting for NYS-procured OSW**	-5,058	-6,226	923	1,303	-3,941	-3,701
Net energy for load	196,255	196,255	227,001	227,001	269,821	269,821

* Pathways 2 and 3 have OSW injected to and delivered from outside areas.

** The 2040 and 2050 NYCA-wide net loads are 227,001 GWh and 269,821 GWh, respectively. After considering the external OSW that are dispatched toward NYISO, the net imports for all Pathways in 2040 and 2050 are less than 2% of NYCA-wide net load. Therefore, for modeling purposes, 2040 and 2050 can be considered to achieve net zero imports for NYISO.

Note: Injections into ISO-NE and PJM were analyzed for deliverability to NYCA, as required by section 2.1.6 of the ORECRFP23-1 Request for Proposals in 2023. The deliverability studies were performed in accordance with PJM Generation Deliverability procedures outlined by PJM Manual 14B and ISO-NE Planning Procedures and ISO-NE Planning Procedure 10. The resulting illustrative transmission expansion portfolio was included in the pathway.

Table C-4. Generation/Imports (gigawatt-hours) by Category - Pathway 3

	2035		2040		2050	
GWh	Radial	Mesh	Radial	Mesh	Radial	Mesh
Nuclear	26,496	26,496	26,496	26,496	16,727	16,727
Hydro	27,478	27,503	25,869	25,876	25,554	25,528
Thermal	35,691	35,773	15,066	15,623	25,789	22,918
Solar	41,209	41,302	59,891	59,950	78,418	78,714
LBW	37,091	37,092	42,291	42,277	53,146	53,221
OSW	37,558	37,561	59,960	60,177	65,993	66,319
Net imports from HQ	16,587	16,582	19,166	19,152	19,112	19,045
OSW generation in PJM/NE					16269	16244
Net imports from PJM, ISO-NE, and IESO, before accounting for NYS-procured OSW injections in those regions	-6,984	-7,022	3,275	2,033	11,825	14,535
NYS-procured OSW in PJM and ISO-NE*	0	0	3,305	3,293	16,269	16,244
Net imports from PJM, ISO-NE, and IESO, after accounting for NYS-procured OSW**	-6,984	-7,022	-31	-1,260	-4,445	-1,709
Net energy for load	196,255	196,255	227,001	227,001	269,821	269,821

* Pathways 2 and 3 have OSW injected to and delivered from outside areas..

** The 2040 and 2050 NYCA-wide net loads are 227,001 GWh and 269,821 GWh, respectively. After considering the external OSW that are dispatched toward NYISO, the net imports for all Pathways in 2040 and 2050 are less than 2% of NYCA-wide net load. Therefore, for modeling purposes, 2040 and 2050 can be considered to achieve net zero imports for NYISO.

Note: Injections into ISO-NE and PJM were analyzed for deliverability to NYCA, as required by section 2.1.6 of the ORECRFP23-1 Request for Proposals in 2023. The deliverability studies were performed in accordance with PJM Generation Deliverability procedures outlined by PJM Manual 14B and ISO-NE Planning Procedures and ISO-NE Planning Procedure 10. The resulting illustrative transmission expansion portfolio was included in the pathway.

Figure C-1. NYCA-Wide Megawatts Net Load Curve for 2035

Net load is calculated as the gross load minus the contributions from BTM-PV.

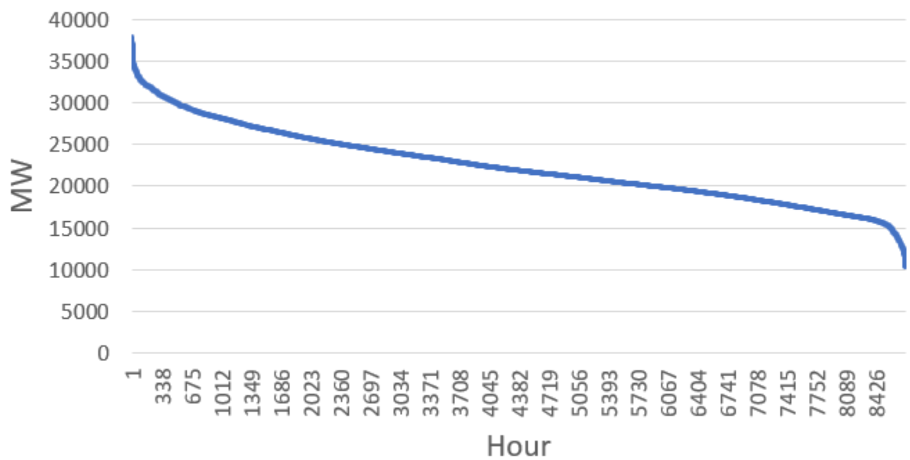


Figure C-2. NYCA-Wide Megawatts Net Load Curve for 2040

Net load is calculated as the gross load minus the contributions from BTM-PV.

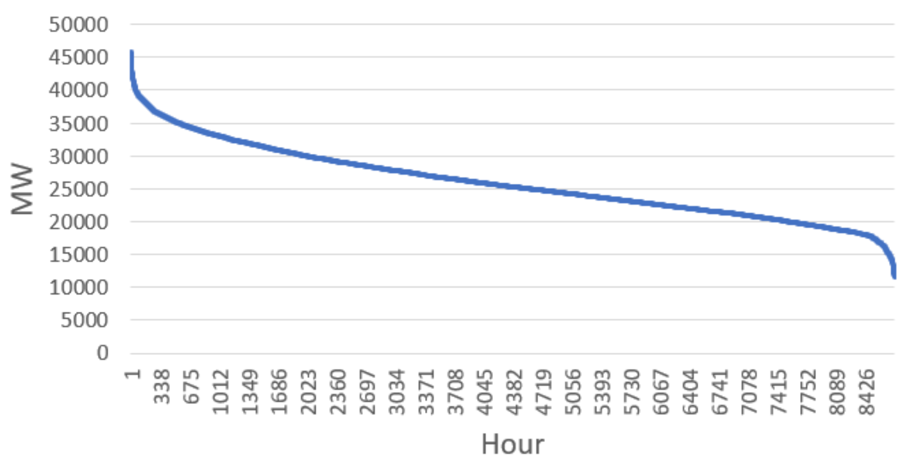
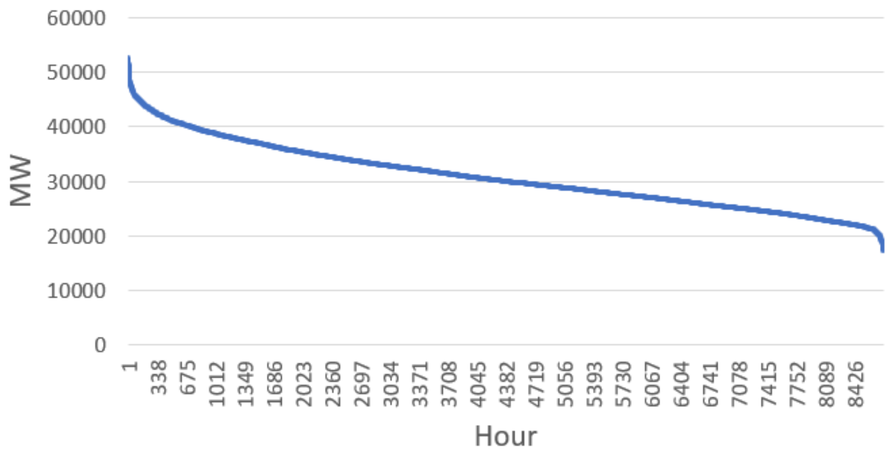


Figure C-3. NYCA-Wide Megawatts Net Load Curve for 2050

Net load is calculated as the gross load minus the contributions from BTM-PV.



Appendix D. 9-Gigawatt Scenario

Appendix D summarizes key assumptions and outcomes from the 9 Gigawatt Scenario.

Table D-1. Offshore Wind Points of Interconnection

Point of Interconnection	Landing Point
Farragut	Zone J
Rainey	Zone J
Gowanus	Zone J
Astoria	Zone J
Barrett	Zone K
Holbrook	Zone K
East Hampton	Zone K
Ruland Road	Zone K
East Garden City	Zone K

Figure D-1. Meshed Design for 9-Gigawatt Scenario

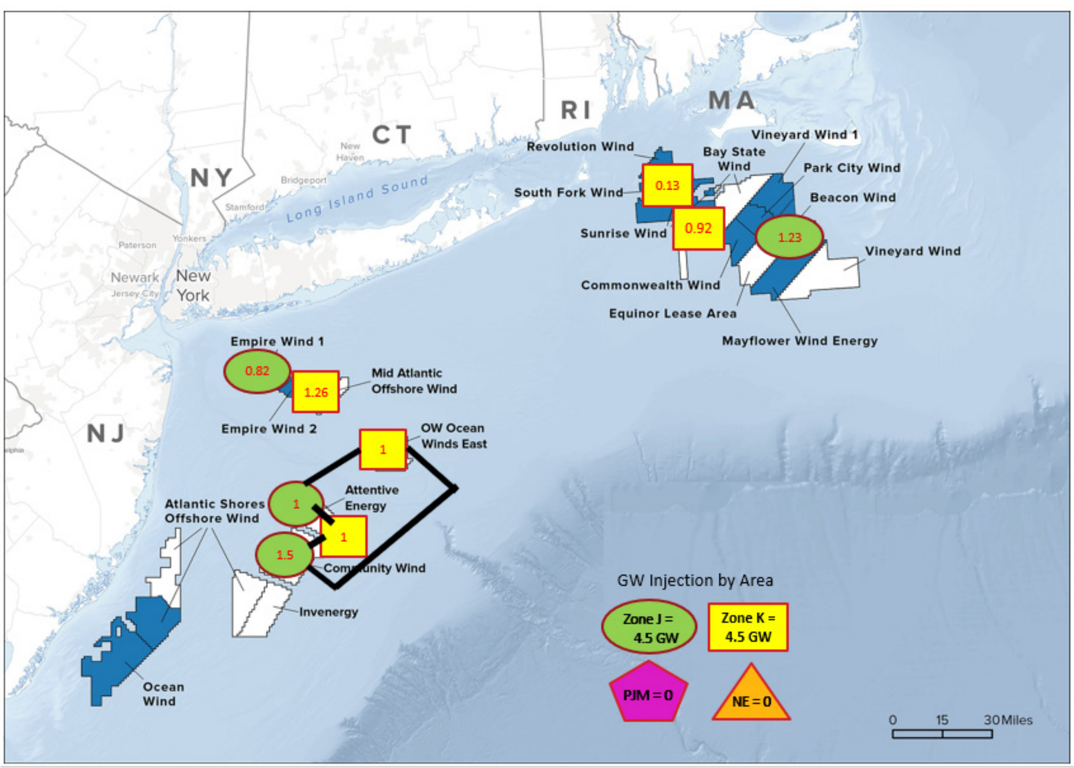


Table D-2. Generation Capacity by Type

Fuel Mix (Capacity)	Unit	2035	2040	2050
Nuclear	MW	3,355	3,355	2,135
Thermal	MW	19,781	23,522	25,359
Hydro	MW	4,613	4,613	4,613
UPV	MW	28,625	48,735	70,891
BTM-PV	MW	12,788	15,764	15,764
LBW	MW	10,668	17,369	23,561
OSW	MW	9,000	9,000	9,000

Table D-3. Generation/Imports (gigawatt-hours) by Category

	2035		2040		2050	
GWh	Radial	Mesh	Radial	Mesh	Radial	Mesh
Nuclear	26,496	26,496	26,496	26,496	16,727	16,727
Hydro	27,585	27,607	25,941	25,997	25,459	25,435
Thermal	35,700	35,828	12,052	11,752	23,747	22,715
Solar	41,305	41,408	70,396	70,481	96,256	96,267
LBW	37,196	37,190	58,746	58,831	75,334	75,345
OSW	37,179	37,231	37,773	37,799	37,618	37,654
Net imports from HQ	16,939	16,939	18,877	18,923	18,212	18,290
Net imports from PJM, ISONE, and IESO	-5,237	-6,401	2,723	3,138	3,520	3,434
Net energy for load	196,255	196,255	227,001	227,001	269,821	269,821

Table D-4. Breakdown of Benefit/Cost Categories

All in 2020 Dollars	
NPV of Benefits ($M)	3,169
NPV of Levelized Total Costs ($M)	1,946
Benefit/Cost Ratio	1.6

All in 2020 Dollars	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Production-Cost Benefits ($M)	21	59	98	136	175	213	208	204	199	195	190
Avoided Curtailment (Availability)($M)	14	14	14	14	14	14	14	14	14	14	14
Avoided Transmission—Levelized Cost ($M)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total Benefits ($M)	35	73	112	150	188	227	222	218	213	208	204
Levelized Investment Costs (including O&M)	106	106	106	106	106	106	106	106	106	106	106
Total Benefits—Levelized Investment Costs	-71	-33	6	44	83	121	116	112	107	102	98
All in 2020 Dollars	**2046**	**2047**	**2048**	**2049**	**2050**	**2051**	**2052**	**2053**	**2054**	**2055**	**2056**
Production-Cost Benefits ($M)	185	181	176	171	167	167	167	167	167	167	167
Avoided Curtailment (Availability)($M)	14	14	14	14	14	14	14	14	14	14	14
Avoided Transmission—Levelized Cost ($M)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total Benefits ($M)	199	195	190	185	181	181	181	181	181	181	181
Levelized Investment Costs (including O&M)	106	106	106	106	106	106	106	106	106	106	106
Total Benefits—Levelized Investment Costs	93	89	84	79	75	75	75	75	75	75	75

Table D-4 (continued)

All in 2020 Dollars	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	
Production-Cost Benefits ($M)	167	167	167	167	167	167	167	167	167	167	167	
Avoided Curtailment (Availability)($M)	14	14	14	14	14	14	14	14	14	14	14	
Avoided Transmission—Levelized Cost ($M)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Total Benefits ($M)	181	181	181	181	181	181	181	181	181	181	181	
Levelized Investment Costs (including O&M)	106	106	106	106	106	106	106	106	106	106	106	
Total Benefits—Levelized Investment Costs	75	75	75	75	75	75	75	75	75	75	75	
All in 2020 Dollars	**2068**	**2069**	**2070**	**2071**	**2072**	**2073**	**2074**	**2075**	**2076**	**2077**	**2078**	**2079**
Production-Cost Benefits ($M)	167	167	167	167	167	167	167	167	167	167	167	167
Avoided Curtailment (Availability)($M)	14	14	14	14	14	14	14	14	14	14	14	14
Avoided Transmission—Levelized Cost ($M)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total Benefits ($M)	181	181	181	181	181	181	181	181	181	181	181	181
Levelized Investment Costs (including O&M)	106	106	106	106	106	106	106	106	106	106	106	106
Total Benefits—Levelized Investment Costs	75	75	75	75	75	75	75	75	75	75	75	75

Note: The negative net benefits during the initial years are indicative of levelized investment costs exceeding the benefits. In the future, the net benefits are positive as the ongoing operational savings and increased efficiencies begin to outweigh the initial investment costs, leading to a more favorable benefit/cost ratio over time.

Endnotes

1 Department of Public Service Order on Power Grid Study Recommendations, January 20, 2022. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={23F0F463-A059-4CFC-9134-4535F660611F}

2 CAC Draft Scoping Plan. December 30, 2021. https://climate.ny.gov/Resources/Draft-Scoping-Plan

3 New York State Energy Research and Development Authority. 2022. "Offshore Wind Solicitation ORECRFP22-1 – Appendix G - Meshed Ready Technical Requirements." https://portal.nyserda.ny.gov/CORE_Solicitation_Document_Page?documentId=a0l8z000000Gzo4&_gl=1*9wg79h*_gcl_au*MTIwOTMzMjgyNS4xNzE1MTAyNDM3*_ga*MTAzOTA5MTI4MS4xNjkwNTY3MjYz*_ga_DRYJB34TXH*MTcxODYzNjQ4MC41MC4xLjE3MTg2MzY3MzMuMzIuMC4w

4 The pathways were developed using information available at the commencement of the study in November 2022. This, among other things, reflected a mix of confirmed contracts, designated lease areas, lease areas currently under negotiation, and specified POIs as they were identified at that time.

5 The benefit/cost method is further described in section 6. The method does not use the benefit/cost analysis framework described in the January 21, 2016, Order Establishing the Benefit/Cost Analysis Framework. Rather, the methodology for this study was developed with input from DPS staff.

6 Atlantic Offshore Wind Transmission Study. https://www.nrel.gov/wind/atlantic-offshore-wind-transmission-study.html

7 Department of Public Service Order on Power Grid Study Recommendations, January 20, 2022. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={23F0F463-A059-4CFC-9134-4535F660611F}

8 More information about meshed offshore wind transmission can be found in section 3 of this report.

9 The pathways were developed using information available at the commencement of study in November 2022. This reflected a mix of confirmed contracts, designated lease areas, lease areas currently under negotiation, and specified POIs as they stood at that time. Although some things have changed since that time, the pathways evaluated in this study still serve as good illustrative comparisons of the benefits and costs of meshed transmission versus a radial transmission approach.

10 Offshore Wind Cable Corridor Constraints Assessment. NYSERDA, 2023. https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Programs/Offshore-Wind/2306-Offshore-Wind-Cable-Corridor-Constraints-Assessment--completeacc.pdf

11 New York State Energy Research and Development Authority. 2022. "Offshore Wind Solicitation ORECRFP22-1 – Appendix G - Meshed Ready Technical Requirements." https://portal.nyserda.ny.gov/CORE_Solicitation_Document_Page?documentId=a0l8z000000Gzo4&_gl=1*9wg79h*_gcl_au*MTIwOTMzMjgyNS4xNzE1MTAyNDM3*_ga*MTAzOTA5MTI4MS4xNjkwNTY3MjYz*_ga_DRYJB34TXH*MTcxODYzNjQ4MC41MC4xLjE3MTg2MzY3MzMuMzIuMC4w

12 Although the largest single contingency limit in New York State is 1,310 MW, the analysis considered OSW injection capacity of up to 2,000 MW. As discussed in section 7 of this report, exceedance of the current single largest contingency limit is subject of further investigation and studies to be performed by the NYISO and neighboring ISOs.

13 CAC Draft Scoping Plan Appendix G: Annex 2: Key Drivers and Outputs. https://climate.ny.gov/Resources/-/media/project/climate/files/IA-Tech-Supplement-Annex-2-Key-Drivers-Outputs.xlsx

14 CIGRE, Survey of Reliability of HVDC Systems. https://www.e-cigre.org/publications/detail/b4-11135-2022-survey-of-the-reliability-of-hvdc-systems-throughout-world-during-2019-2020.html

15 "The Benefit and Cost of Preserving the Option to Create a Meshed Offshore Grid for New York," study prepared by The Brattle Group for NYSERDA, filed with its comments in Case 20- E-0197 on November 24, 2021.

16 The O&M costs have been developed in coordination with vendors under a predefined set of assumptions that include periods where scheduled maintenance is to be performed, coordination directives with the wind turbine maintenance, type of maintenance (visual versus condition), annual versus biannual, and the expected life of the assets.

17 The DPS Office of Accounting, Audits and Finance established the real discount rate of 4.78% per year, revised Feb. 8, 2023.

18 The resources that will be eligible to meet 2040 requirements of the Climate Act are uncertain. For this study, the dispatchable emissions-free generation was assumed to be hydrogen combustion turbines. As noted in the New York Power Grid Study, other forms of clean generation or long-duration storage could also provide these services. Although we did not model a scenario with changes to the fuel prices to represent these other clean technologies, the Atlantic Offshore Wind Transmission Study did find that the benefit/cost conclusions related to networked transmission were robust to different clean fuel prices. This analysis assumes out-of-state cost of hydrogen, consistent with the CAC Draft Scoping Plan Appendix G: Annex 1: Inputs and Assumptions XLSX.

NYSERDA, a public benefit corporation, offers objective information and analysis, innovative programs, technical expertise, and support to help New Yorkers increase energy efficiency, save money, use renewable energy, and reduce reliance on fossil fuels. NYSERDA professionals work to protect the environment and create clean-energy jobs. NYSERDA has been developing partnerships to advance innovative energy solutions in New York State since 1975.

To learn more about NYSERDA's programs and funding opportunities, visit nyserda.ny.gov or follow us on X, Facebook, YouTube, or Instagram.

New York State Energy Research and Development Authority

17 Columbia Circle
Albany, NY 12203-6399

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

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