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Atlantic Offshore Wind Transmission Study

EXECUTIVE SUMMARY

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Disclaimer

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Executive Summary

Offshore wind energy continues to grow in the U.S. Atlantic. In 2023, there were 41 gigawatts (GW) in East Coast project pipelines (Musial et al. 2023),[1] driven partly by state-level policies that incentivize offshore wind development. The Biden-Harris administration has set a national goal of deploying 30 GW of offshore wind energy by 2030 (The White House 2021), which would unlock a pathway to 110 GW or more by 2050. Ensuring adequate, equitable, affordable, and timely transmission access for offshore wind energy is critical to achieving state- and national-level goals.

The Atlantic Offshore Wind Transmission Study (AOSWTS) is part of the U.S. Department of Energy's (DOE) efforts to understand and facilitate the transmission of electricity from wind in the Atlantic Ocean. It was informed by the *Atlantic Offshore Wind Transmission Literature Review and Gaps Analysis* (Bothwell et al. 2021) and the convening workshops hosted in 2022–2023 by DOE and the U.S. Department of the Interior's Bureau of Ocean Energy Management. The study results help to inform *An Action Plan for Offshore Wind Transmission Development in the U.S. Atlantic Region* (Baker et al. 2024). DOE's Wind Energy Technologies Office funded AOSWTS.

The AOSWTS identifies and evaluates pathways to enable offshore wind energy deployment in the Atlantic Ocean through coordinated offshore transmission solutions in the near term (by 2030) and long term (by 2050). The study fills gaps in prior analyses by providing a multiregional planning perspective that evaluates offshore wind generation development with transmission planning. It incorporates environmental, ocean co-use, and other siting considerations into defining potential offshore transmission routes. The study also compares different multiregional offshore transmission topologies and their associated costs (using potential cable routes) and benefits (in terms of production cost[2] savings and enhanced resource adequacy).[3] In addition, the AOSWTS analyzes reliability impacts from a multiregional perspective.

The study provides guidance for policymakers and transmission stakeholders on possible outcomes resulting from a proactive, coordinated, and interregional approach to transmission planning for offshore wind energy development in the Atlantic. While this study presents possibilities, additional work following system operator methods and procedures can help build on this analysis.

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[1] https://www.energy.gov/sites/default/files/2023-08/offshore-wind-market-report-2023-edition-data.xlsx, data collected by May 31, 2023

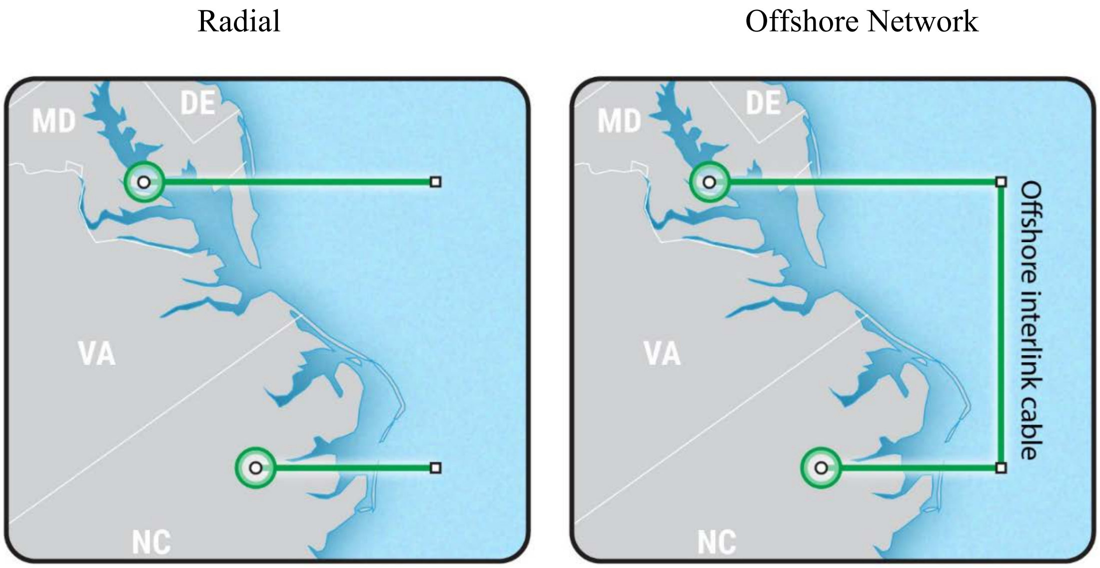
[2] Production costs are the operational costs of producing electricity, including fuel, operations and maintenance, and startup costs.

[3] Resource adequacy is the ability of a power system to generate electricity to meet demand with sufficiently low risk of needing emergency measures. Resource adequacy is one part of reliability.

Study Methods

With input from a technical review committee, the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory designed the AOSWTS to address important questions about transmission infrastructure to advance offshore wind energy development and the impact on regional and interregional electricity delivery costs. The study includes:

- Analysis of offshore substation and cable costs for five different offshore transmission topologies. These topologies comprise different layouts of cables that interlink between offshore wind platforms to form an offshore network (see Figure ES-1). The reference configuration is the radial topology, in which there are no interlinking cables, and each offshore platform connects directly to an onshore location.
- Development and use of a tool and datasets that incorporate 26 environmental siting layers to determine and optimize potential offshore cable routes considering economics and ocean co-uses.
- Evaluation of the production cost benefits using more than a dozen sensitivities on a 2050 low-carbon grid with 85 GW of offshore wind capacity from Maine through South Carolina.
- Grid reliability modeling, including resource adequacy, power flow, grid strength, and contingency analysis.
- Identification of a potential transmission expansion sequence that achieves benefits, considers near-term plans for deployment, and optimizes long-term transmission planning consistent with technology trends for offshore transmission.



Radial

Offshore Network

Figure ES-1. Diagram of radial (left) vs. networked (right) offshore transmission. ***Figure by NREL***

The analysis for this study focuses on the offshore space between Maine and South Carolina and the onshore grid in those states (plus Vermont and Pennsylvania due to proximity). The entire Eastern Interconnection grid is considered in the capacity expansion, resource adequacy, production cost, and reliability modeling.

Key Findings

Offshore wind energy development provides a unique opportunity to add transmission capacity offshore that provides value to the electric grid. Key findings of the study include:

- Offshore wind energy is projected to be a key part of achieving a low-carbon future for Atlantic states.
- Offshore transmission can be planned while considering ocean co-uses and environmental constraints.
- Benefits of networking offshore transmission come from reduced curtailment, reduced usage of higher-cost generators, and contributions to reliability.
- Offshore transmission networks contribute to grid reliability by enabling resource adequacy and helping manage the unexpected loss of grid components (contingencies).
- Benefits of offshore transmission networking outweigh the costs, often by a ratio of 2 to 1 or more. Offshore networks with interregional interlinks provide the highest value.
- Building offshore transmission in phases can help reduce development risk, but early implementation of high-voltage direct current (HVDC) technology standards is essential for future interoperability.

Offshore wind energy is projected to be a key part of achieving a low-carbon future for Atlantic states.

The electricity sector uses capacity expansion models to simulate and analyze the future expansion of generation and transmission capacity to meet expected loads. NREL's Regional Energy Deployment System capacity expansion model develops business-as-usual (BAU) and low-carbon (95% carbon-dioxide reduction from 2005 levels) generation capacity scenarios through 2050. The BAU scenario expands land-based wind energy, solar photovoltaics, and energy storage. The low-carbon scenario constructs 85 GW of offshore wind in the Atlantic, along with significant capacity expansion of land-based wind, solar photovoltaics, energy storage, hydrogen combustion turbines, and natural gas with carbon capture and sequestration in 2050. Electricity demand is significantly higher in the low-carbon scenario because of electrification of end uses like space heating to decarbonize these applications. This scenario is used to compare the cost, benefits, and reliability impacts of the various transmission topologies with significant long-term offshore wind energy development.

All 2050 topology analyses leverage the low-carbon scenario and include approximately 27 GW of offshore wind injection into the service area of the Independent System Operator of New England (ISO-NE) from Maine to Connecticut, 19 GW into the New York Independent System Operator (NYISO), 26 GW into the PJM Interconnection (PJM) area from New Jersey to Virginia and North Carolina (PJM-Atlantic), and 13 GW into the SERC Reliability Corporation (SERC) that serves North and South Carolina (SERC-Carolinas). Interlink cables that connect platforms between these regions are considered interregional.

Figure ES-2 shows the fractions of generation from energy sources in different regions in 2050, resulting from the capacity expansion modeling. Capacity expansion modeling results in 2050 show a transition to different mixes of low-carbon generation resources across Atlantic regions. The share of generation from offshore wind increases at a higher latitude: the northern three regions have more than 20% of electricity generation from offshore wind, and ISO-NE's offshore wind generation share is the largest with more than 40%.

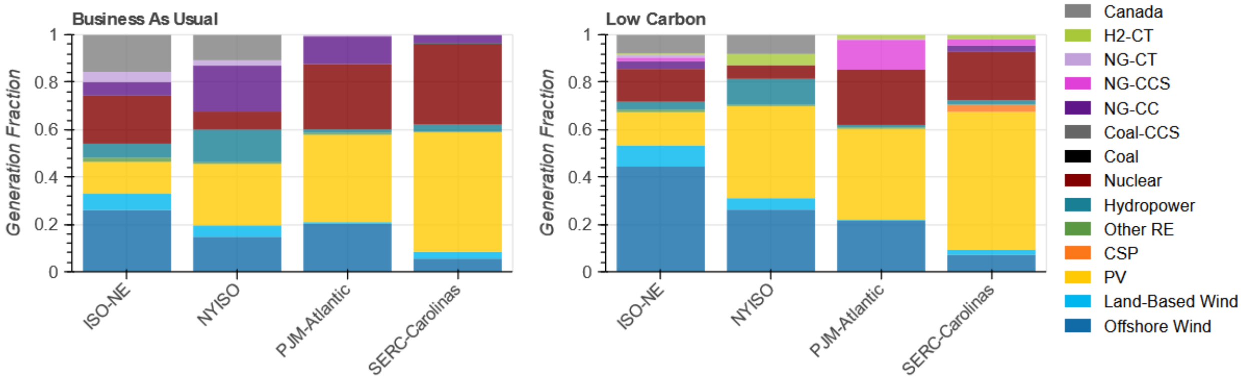


Figure ES-2. 2050 electricity generation fractions from capacity expansion modeling. ***Figure by NREL***

Note: H2-CT = hydrogen combustion turbine; NG-CT = natural-gas combustion turbine; NG-CCS = natural-gas combined cycle with carbon capture and sequestration NG-CC = natural-gas combined cycle; Coal-CCS = coal with carbon capture and sequestration; Other RE = other renewable energy, including biopower and geothermal; CSP = concentrating solar power; PV = photovoltaics. PJM-Atlantic includes the states of PJM that touch the Atlantic Ocean, SERC-Carolinas includes most of North and South Carolina. The electricity demand is significantly larger in the low-carbon scenario due to electrification.

Offshore transmission can be planned while considering ocean co-uses and environmental constraints.

The project team developed the AOSWTS' offshore transmission, including export cables and interlinks, by considering routes' potential to reduce environmental impacts and promote ocean co-uses (other uses of the ocean, such as shipping, fishing, military operations, and so on). The team identified hypothetical cable routes based on 26 data layers, including shipping, military, conservation, sand borrow and placement (for erosion management), and other considerations. While this was not a comprehensive siting study, the analysis identifies potentially feasible corridors within the co-use and environmental constraints.

The team developed cable routes by balancing between maximizing the quality of the wind resource and minimizing the length of the potential export cable route to suitable points of interconnection (POIs) within the previously mentioned co-use and environmental constraints. These routes and POIs are not intended to be a prescription or suggestion for precise locations, but provide a useful suite of POIs for further analysis.

Offshore wind energy development provides a unique opportunity to add transmission capacity offshore to provide value to the grid.

Because the grid in the Atlantic regions is heavily congested in a high-demand, high-renewable 2050 future, offshore transmission infrastructure can be leveraged by interlinking platforms to reduce overall system costs. In modeled estimates using the radial topology in 2050, price differences between suitable POIs for offshore wind averaged over $100/megawatt-hour. This price difference is higher than the average wholesale electricity prices in recent years in some Atlantic market regions. High price differences indicate that offshore transmission with interlinking platforms can consistently flow power from lower- to higher-price regions to benefit electricity consumers by reducing the costs of generating electricity.

In addition to the foundational radial topology, the AOSWTS team evaluated four networked topologies: intraregional, interregional, inter-intra, and backbone, as described here. A simplified representation of three topologies is shown in Figure ES-3, and additional images of these topologies can be found in Section 4 in the main report.

- The radial topology comprises connections from offshore substations to the onshore grid, with no interlinking between offshore platforms (see Figure ES-1). This topology (and its associated export cables) is the basis for all other topologies and is the status quo today for offshore wind generation development in the U.S. Atlantic.
- The intraregional topology focuses on connections within regions that could complement (and come before) interregional solutions.
- The interregional topology is specifically designed to leverage opportunities to connect diverse regions by interlinking offshore platforms.
- The inter-intra topology combines the interlinks in the interregional and intraregional topologies.
- The backbone topology starts with the interregional build and includes an additional cable that spans the studied portion of the Atlantic Seaboard, from Maine through South Carolina.

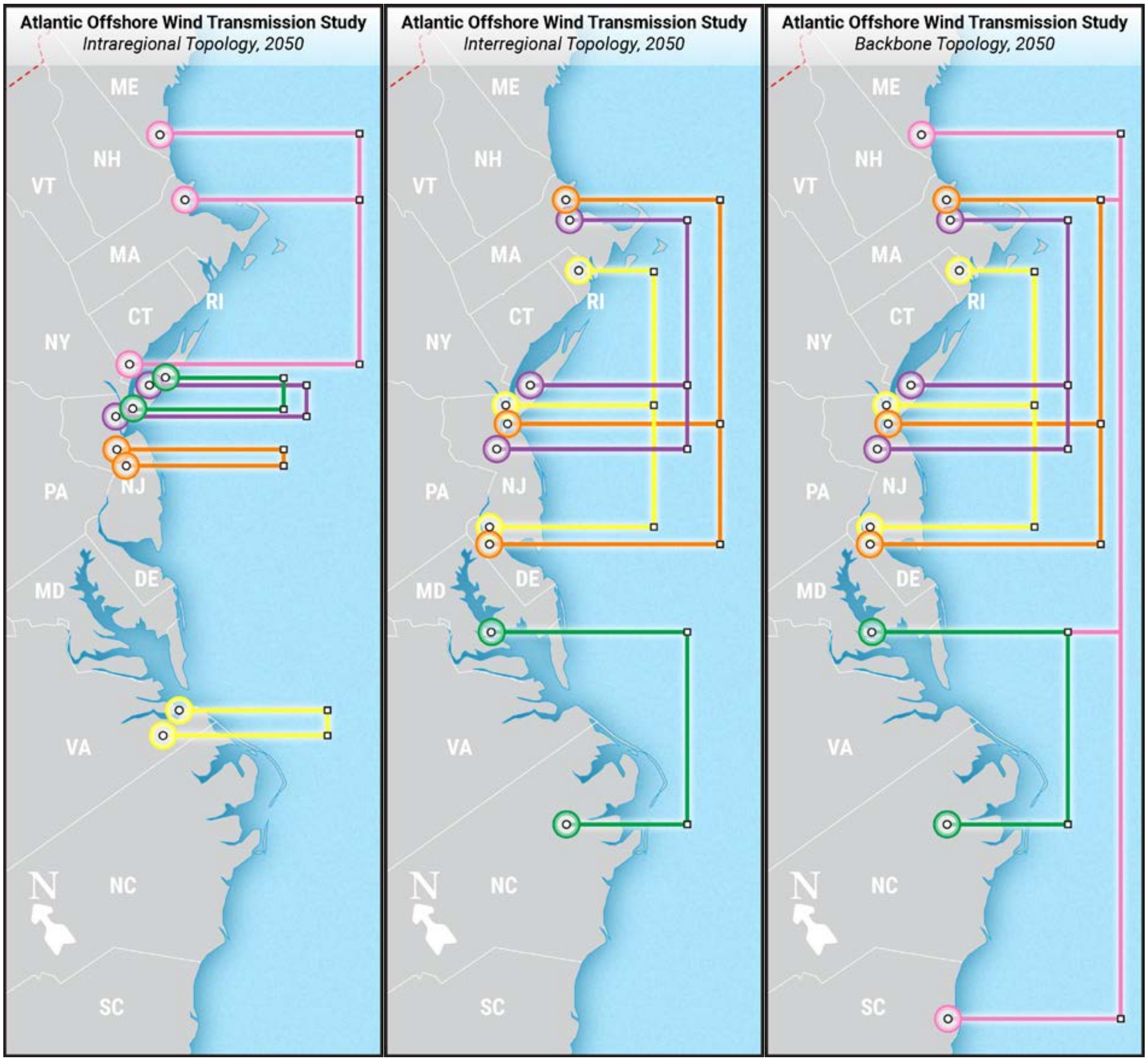


Figure ES-3. Intraregional, interregional, and backbone topologies. ***Illustration by Billy Roberts, NREL***

Note: The inter-intra topology combines the interlinks in the interregional and intraregional topologies, and thus is not shown here.

The interregional transmission expansion, with seven new cables interlinking 11 platforms and providing 14 GW of interregional capacity, is shown in Figure ES-4. Interconnecting offshore wind substations creates networked offshore transmission systems that can be used by multiple offshore and onshore generation resources. The study did not consider any networked topologies that “overbuild” the export cables to enable additional power flows even when the offshore wind is generating at full capacity. All interregional interlinks are 525-kilovolt HVDC technology, whereas the intraregional interlinks are assumed to be 525-kilovolt HVDC in New England, and high-voltage alternating current elsewhere.

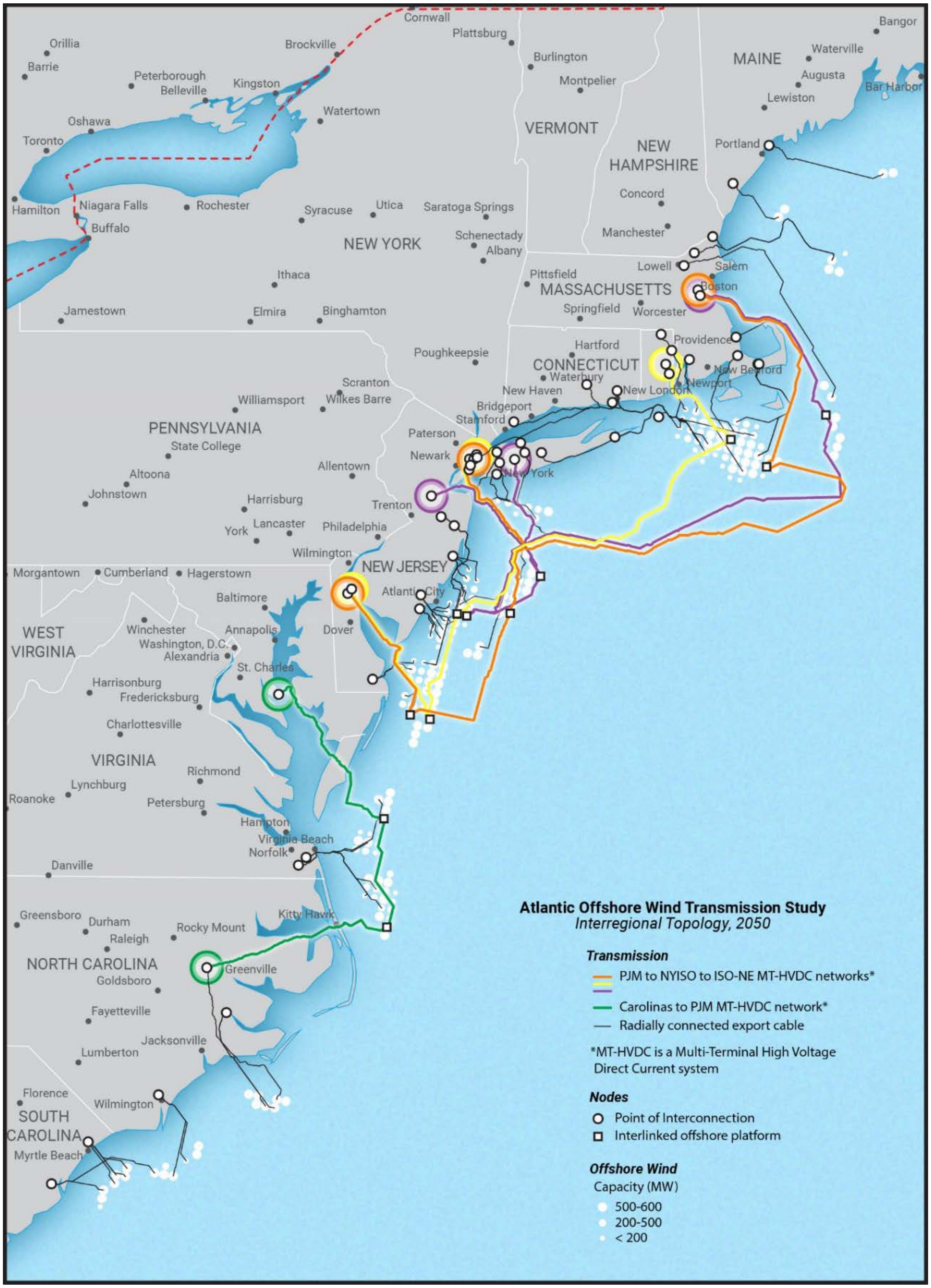


Figure ES-4. The 2050 interregional topology with modeled cable routes. *Illustration by Billy Roberts, NREL*

Benefits of networking offshore transmission come from reduced curtailment, reduced usage of higher-cost generators, and contributions to reliability.

Figure ES-5 shows the total economic value in 2050 for each interlinked transmission topology compared to the radial topology, and the breakdown of the value by category. Most of the benefits are production cost savings (which include fuel, operations and maintenance [O&M], and startup and shutdown costs).

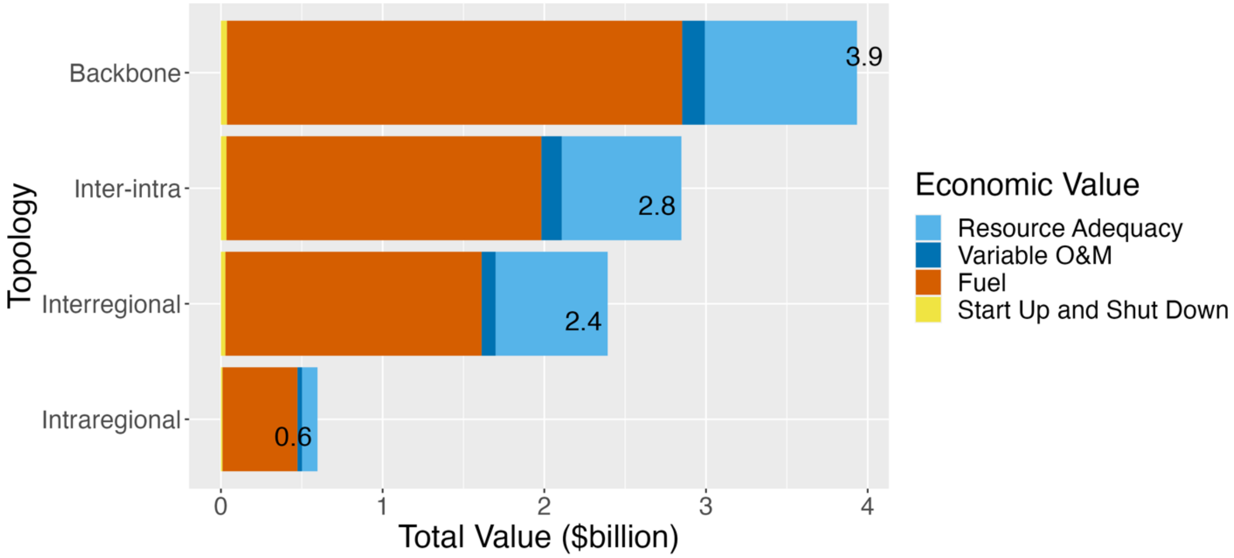


Figure ES-5. Grid benefits from interlinked offshore transmission in 2050. *Figure by NREL*

In addition to economic benefits, AOSWTS modeling showed that flows on all interlinks go both directions every season, reducing overall generation costs and curtailment of offshore wind. The average utilization rate on each line is 50%–60% of the available capacity. Offshore wind curtailment is 1–2 percentage points lower when offshore wind generation is interconnected with interregional interlinks compared with the radial topology.

Offshore transmission networks contribute to grid reliability by enabling resource adequacy and helping manage the unexpected loss of grid components (contingencies).

Resource Adequacy

Improved connection between geographically diverse generation resources using offshore transmission can displace generation investment. Resource adequacy value in 2050 accrues during winter-peaking conditions in colder, electrified Atlantic regions like PJM, NYISO, and ISO-NE when additional transmission capacity can be used to flow power from adjacent regions. Results on the quantity of displaced equivalent firm capacity[4] built in those regions from offshore interlinks are in Table ES-1.

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[4] Equivalent firm capacity results can be interpreted as the quantity of perfect (100% available) generation capacity built (e.g., in megawatts) that can be displaced by resource (e.g., offshore transmission) investment while achieving the same level of systemwide resource adequacy.

Table ES-1. Equivalent Firm Capacity Result

Topology	Quantity of Offshore Interlink Transmission Built (megawatts [MW])	Equivalent Firm Capacity (Potential Displaced Generation) (MW)
Intraregional	7,600	565–664
Interregional	14,000	4,062–4,726
Inter-Intra	21,600	4,453–5,000
Backbone	20,000	5,859–6,250
Intraregional	7,600	565–664

Other Aspects of Reliability

The team conducted a high-level assessment of the potential impacts of offshore wind energy and related offshore transmission infrastructure on system reliability. This effort does not represent a comprehensive system reliability analysis for 30 GW of offshore wind in 2030 and 85 GW of offshore wind in 2050, but rather indicates some of the challenges and opportunities for offshore wind transmission. Conclusions from the reliability analysis include the following:

- Grid strength analysis of 30 GW of offshore wind capacity in 2030 shows that 14 of 24 considered POIs experience weak grid strength conditions. This does not mean the evaluated POIs are infeasible but indicates further studies (and possibly additional investment) are needed to ensure stable and reliable operation of the offshore wind power plant (or any inverter-based resource) under weak grid conditions.
- Dynamic and AC contingency analyses for 30 GW of offshore wind in 2030 do not indicate any widespread issues with maintaining reliability.
- A case study contingency analysis of the interregional topology in 2050 indicates potential benefits of interlinked offshore network topologies to system reliability by enabling mutual support between the onshore and offshore networks during contingency events.
- Developing 85 GW of Atlantic offshore wind capacity may expose the power system to additional resilience risks resulting from extreme weather events occurring in the ocean and at the landing point. To enable improved planning for resilient offshore wind energy integration, the team developed datasets and methods to translate extreme weather events into simulations for both steady-state and dynamic analyses.

Benefits of offshore transmission networking outweigh the costs, often by a ratio of 2 to 1 or more. Offshore networks with interregional interlinks provide the highest value.

Table ES-2 shows the capital costs of offshore transmission infrastructure (including platform costs, circuit breakers, export cables, and interlink cables) in each topology. The total cost for each networked topology also includes $96.3 billion in capital costs for the radial topology that connects the offshore wind generation to the onshore grid. The onshore grid was assumed to be identical when comparing the topologies.

Table ES-2. Offshore Transmission Capital Costs

Topology	Total Cost	Additional Costs Vs. Radial
Radial	$96.3 billion	Not applicable
Intraregional	$99.9 billion	$3.6 billion
Interregional	$107.7 billion	$11.4 billion
Inter-Intra	$111.2 billion	$14.9 billion
Backbone	$116.3 billion	$20.0 billion

Note: These numbers are total capital costs, not annualized costs. All values are in 2021 U.S. dollars.

Table ES-3 presents the annual costs, benefits, net value, and benefit-to-cost ratios for each interlinked topology (compared to the radial topology) in 2050. All networked topologies studied have more benefits than costs of adding transmission interlinks when compared to the radial topology. Offshore networks with interregional interlinks provide the most value as quantified in benefit-to-cost ratios and total net value. Investment in offshore wind energy development—including HVDC converter stations, export cables, platforms, and grid interconnection costs—can be leveraged by interlinking between the platforms. The benefits of offshore networking persist when mixing interregional and intraregional interlinks, along with some radial connections.

Table ES-3. Annual Offshore Transmission Costs and Benefits of the Networked Topologies (Compared to Radial) in 2050

Topology	Annual Offshore Networking Costs ($ million)	Annual Gross Benefit ($ million)	Net Annual Value ($ million) [Benefits - Costs]	Benefit-to-Cost Ratio [Benefits/Costs]
Intraregional	260	590	330	2.3
Interregional	840	2,400	1,560	2.9
Inter-Intra	1,090	2,850	1,760	2.6
Backbone	1,470	3,940	2,470	2.7

Note: Costs in this table represent the additional annualized capital costs and operations and maintenance costs of the networked topologies compared to the radial topology. Benefits represent the 2050 annual production cost and resource adequacy value in the networked topologies compared to the radial topology.

The cost-and-benefit analysis shows the net value for the portfolio of offshore transmission investments identified in the AOSWTS rather than evaluating individual projects or transmission corridors. The economic benefits of interlinked offshore transmission are based on avoided system costs for each transmission scenario compared to the radial topology. These savings include avoided production costs and avoided costs to meet resource adequacy requirements.

The team conducted additional analysis to test various assumptions, including cable capacity, fuel prices, onshore transmission expansion, and the way the offshore network is operated. Benefit-to-cost ratios were positive for the interregional offshore network topology in all variations. Adding high-voltage east-west land-based transmission in the mid-Atlantic region (PJM) provides the largest increase in value. Limiting offshore cable maximum flows to 1,200 megawatts (consistent with current system limitations) offers the largest decrease in value. This additional analysis helps provide confidence in the study results. However, uncertainty in the evolution of the grid means that further study is needed by transmission planners to understand evolving conditions and to build on the data, tools, and methodologies developed in this study. Sections 5 and 6 in the main report describe these scenarios in more detail.

Building the offshore transmission in phases can help reduce development risk, but early implementation of HVDC technology standards is essential for future interoperability.

The AOSWTS assumes a planning trajectory that considers interoperable, multiterminal HVDC technology available for offshore transmission starting in the mid-2030s. Offshore wind energy development planned for operation by 2030 does not include multiterminal HVDC readiness. These assumptions are consistent with current offshore wind project procurements and their timelines (Pfeifenberger et al. 2023). The studied interregional and backbone topologies require multiterminal HVDC technology to be available and implemented on offshore platforms (which would need to be designed for potential future interlinking) by 2035.

The study team considered a possible phased approach for offshore transmission development. This order of offshore transmission, shown in Figure ES-6, is based on interlinking projects as they are developed and available to interlink, with more favorable projects developed earlier, considering wind resource, cable distance, and state targets. This phasing of offshore transmission development can use infrastructure development capabilities efficiently but requires a consistent HVDC technology standard to enable multiterminal, multivendor interoperability. Defining a common interoperability standard before HVDC is deployed in topologies like the interregional scenario will be critical to meeting the development timelines and achieving the benefits quantified in this study.

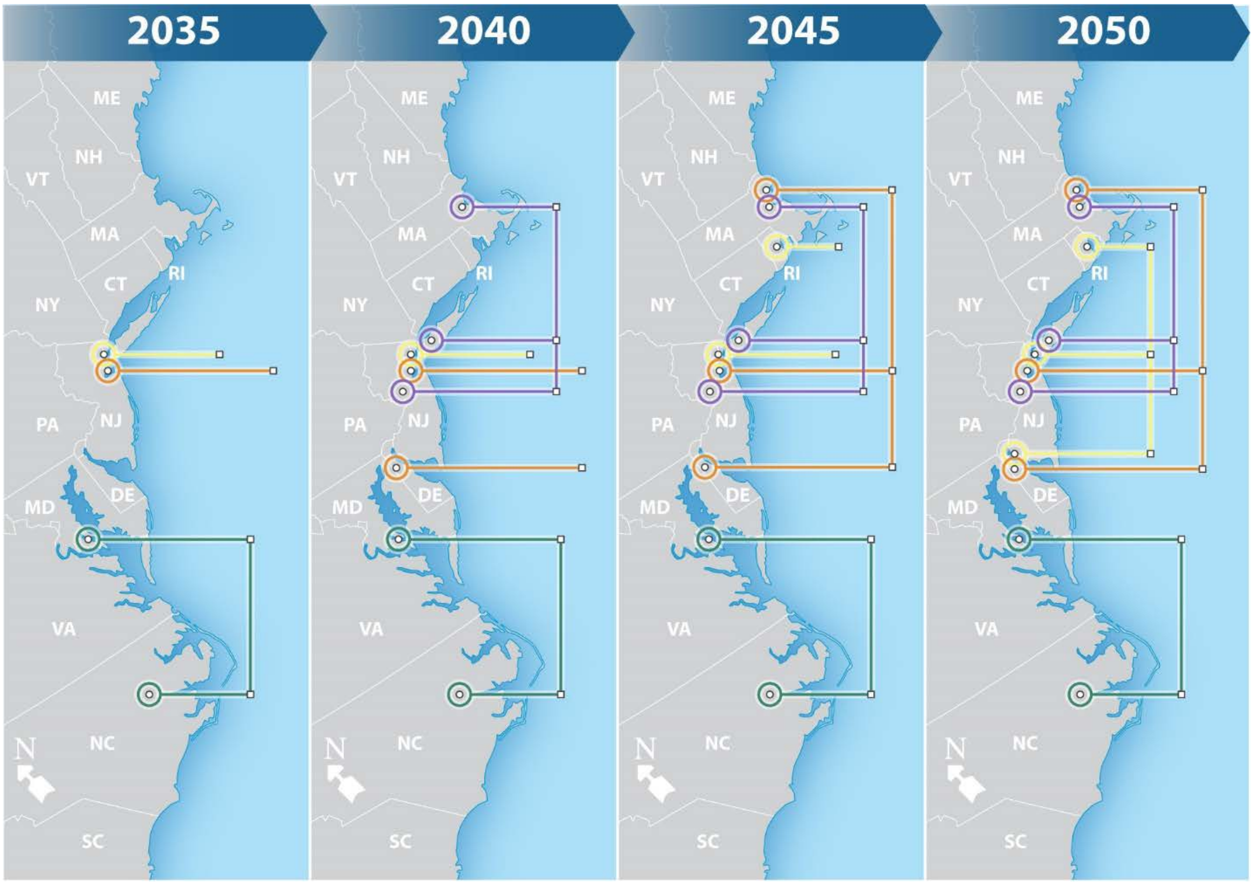

Figure ES-6. Potential build timeline of the interregional topology. ***Illustration by Billy Roberts and Al Hicks, NREL***

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