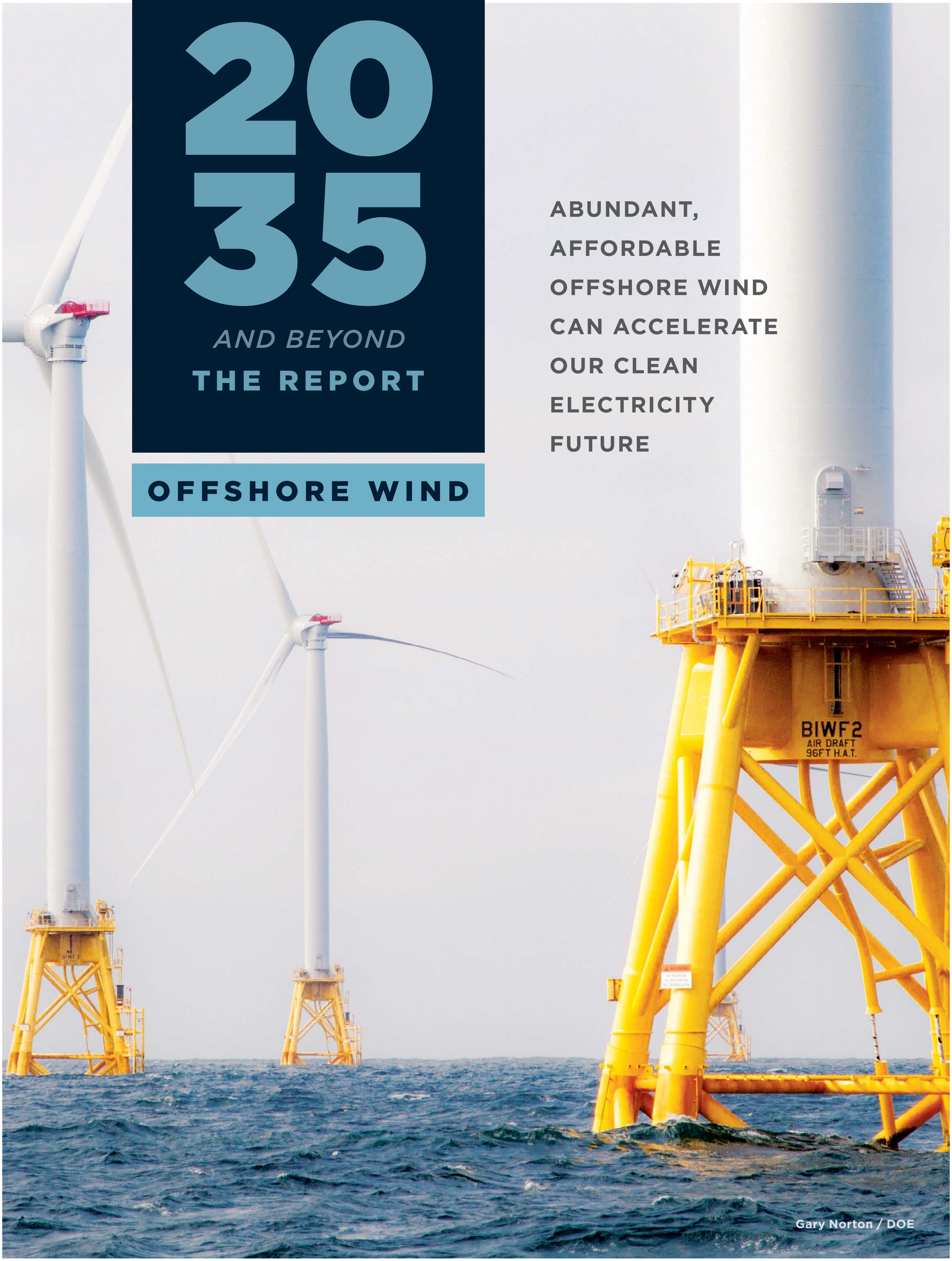
2035 AND BEYOND

THE REPORT

OFFSHORE WIND

ABUNDANT, AFFORDABLE OFFSHORE WIND CAN ACCELERATE OUR CLEAN ELECTRICITY FUTURE



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EXECUTIVE SUMMARY

Plummeting costs and technical performance improvements of offshore wind have dramatically enhanced the prospects for near-term power sector decarbonization. The high resource quality of offshore wind in the United States, coupled with rapidly falling technology costs, makes it possible for offshore wind to provide 10-25% of total electricity generation in the U.S. power system in 2050 without substantially impacting wholesale electricity costs. This report, 2035 Report 3.0, examines the prospect of achieving 90% clean electricity by 2035 and 95% clean electricity by 2050. Three scenarios — Low, Medium, and High Ambition — detail the electricity system impacts of increased offshore wind growth providing 10-25% of total generation.

Global carbon emissions must be halved by 2030 to limit global warming to 1.5 degrees Celsius and avoid the most catastrophic impacts of climate change (UN IPCC, 2023). While the United States continues to make progress on national decarbonization trends, with increases in clean energy production delivering cuts in power sector emissions, 2022 still saw a slight rise in the nation's overall greenhouse gas emissions (Rhodium Group, 2023). For the U.S. to achieve net zero emissions, in which the nation emits no more carbon into the atmosphere than can be removed, the U.S. must significantly ramp up clean energy production while electrifying other sectors of the economy, such as buildings, transportation, and industry — likely causing U.S. electricity demand to triple by 2050.

Dennis Schroeder / NREL

Around the globe, nations have begun to grasp the opportunity on the waters. The global pipeline of offshore wind projects that have been announced or are in pre-construction phases now stands at over 700 GW (GEM, 2023). The European Union will endeavor to build nearly 400 GW of offshore wind by 2050, while China installed 20 GW in the last two years alone (European Commission, 2023; GWEC, 2023). While the Biden Administration has a target to deploy 30 GW of offshore wind by 2030 and 110 GW by 2050, increasing offshore wind ambition beyond these current goals could accelerate the nation's transition to net zero emissions.

THE UNITED STATES HAS HIGH-QUALITY AND ABUNDANT OFFSHORE WIND POTENTIAL

The United States has some of the highest offshore wind potential in the world. When combined, the U.S. coastline, including the Great Lakes region, has the technical potential of nearly 4,000 GW of offshore wind capacity. Over 1,000 GW of this potential is highly productive, with capacity factors above 50%, suggesting offshore wind can provide affordable and reliable clean energy generation across the nation.

OFFSHORE WIND CAN BE INTEGRATED INTO THE U.S. POWER GRID WITHOUT IMPACTING WHOLESALE ELECTRICITY COSTS

Offshore wind costs have dropped rapidly over the past few years, and the Department of Energy (DOE) forecasts prices to fall to $53/MWh by 2035, cheaper than the levelized cost of a new combined cycle gas plant or coal plant, and on par with existing solar and wind projects (WETO, 2023). As a result of improved performance and falling costs, wholesale electricity costs (the cost of generation plus new transmission) are comparable in all Offshore Wind Policy scenarios. Wholesale electricity costs in the High Ambition scenario, in which the nation deploys 750 GW of offshore wind by 2050, are just 2.2% higher in 2035 than a Baseline scenario with minimal offshore wind deployment and 0.25% higher than Baseline in 2050. Wholesale electricity costs in the Low and Medium Ambition offshore wind scenarios are both lower than Baseline in 2050.

OFFSHORE WIND COMPLEMENTS LAND-BASED RENEWABLES TO MEET INCREASED ELECTRICITY DEMAND IN A NET ZERO ECONOMY

To achieve net zero carbon emissions economy-wide requires the elimination of fossil fuels and the transition to electric end-uses (such as electric vehicles and heat pumps), which will likely lead to a tripling in electricity demand by 2050. The nation will have to significantly increase annual deployments of clean energy resources and expand the available suite of technologies in order to meet future clean energy generation needs. An expanded commitment to offshore wind could bolster the technology such that offshore wind could support 10-25% of the nation's electricity demand by 2050.

Achieving net zero emissions in the U.S. requires the installation of over 3,500 GW of new renewable resources through 2050. The annual deployment targets across all scenarios are ambitious, requiring 100 GW of new land-based solar and wind deployed each year through 2050 on average, and nearly 40 GW of new offshore wind each year between 2035-2050. While the U.S. installed a record 28 GW of renewable capacity in 2021, achieving net zero goals without offshore wind will require the nation to install land-based wind and solar at five times that rate. Increasing offshore wind deployments would reduce the land-based installation rate to three or four times 2021 levels.

SCALING THE OFFSHORE WIND SUPPLY CHAIN WILL REQUIRE SIGNIFICANT CAPITAL INVESTMENT AND ROBUST DOMESTIC POLICY SUPPORT

The development of a robust offshore wind domestic supply chain is a necessary step towards achieving the United States' ambitious clean energy goals. While researchers have identified a pathway to developing the supply chains needed to support the Biden Administration's 30 GW by 2030 target, scaling the offshore wind industry beyond that will require targeted domestic policy support and infrastructure investment. In order for offshore wind to provide 10-25% of the nation's electricity needs, cumulative investment in the supply chain would need to exceed $260 billion through 2045. Manufacturing the amount of blades, nacelles, towers, and cables required to meet the Medium and High Ambition targets will require a four or five fold increase in the estimated number of facilities needed to meet the 30 GW by 2030 target. Lack of port capacity and wind turbine installation vessels will likely remain the largest bottleneck to scaling the U.S. offshore wind industry.

HIGH-QUALITY OFFSHORE WIND IS AVAILABLE ACROSS ALL COASTAL STATES, EXPANDING THE AREA AVAILABLE FOR DEPLOYMENT WHILE DISPERSING ECONOMIC BENEFITS ACROSS THE NATION

The U.S. is fortunate in its abundant coastline and high-quality wind potential across all major coastal areas. The quality of the offshore wind resource suggests that the U.S. can deploy significant new offshore wind capacity along the U.S. coastline, bringing clean energy and the accompanying economic benefits to a majority of the population. As offshore wind deployment increases, the area directly impacted by renewable energy infrastructure decreases relative to the Baseline scenario. Because of the high power density of offshore wind resources, the U.S. could generate more clean power on a smaller footprint offshore.

COORDINATED TRANSMISSION PLANNING CAN REDUCE INTERCONNECTION COSTS AND ACCELERATE DEPLOYMENT TIMELINES

A net zero electricity grid will require significant new investment in transmission infrastructure in order to distribute clean energy generation across the nation. The transition to net zero will require doubling existing transmission infrastructure. By clustering multiple offshore wind farms together and connecting them to the onshore grid using a single, high-voltage transmission line, offshore transmission investments can be reduced by approximately 35% relative to a business-as-usual transmission approach. Clustering enables developers to build fewer, higher capacity lines which reduces total assets and minimizes energy losses. Offshore wind provides an opportunity to reimagine the transmission planning process and avoid the bottlenecks that have plagued land-based renewable energy deployment.

OFFSHORE WIND GENERATION CAN SUPPORT A DEPENDABLE GRID TO MEET NEAR-NET ZERO EMISSIONS

A diverse portfolio of clean energy technologies, bolstered by highly productive and widely deployed offshore wind, is critical to ensuring future grid dependability with the anticipated increase in energy demand through 2050. Not only is offshore wind an abundant resource, its generation patterns are particularly complementary to existing land-based wind and solar and well-matched to electricity demand trends. Over the course of an average year, offshore wind can pair with other clean resources to provide nearly 95% of total electricity generation in 2050.

SCALING THE DOMESTIC OFFSHORE WIND INDUSTRY COULD CREATE NEARLY 390,000 JOBS AND SPUR ECONOMIC ACTIVITY ACROSS THE COUNTRY

When isolating the impacts of just offshore wind development, the High Ambition offshore wind policy scenario could support approximately 390,000 jobs across the economy in 2050. A scenario in which a greater percentage of goods and materials are sourced domestically — a policy goal of the Inflation Reduction Act — leads to additional job creation, while expanding employment and economic benefits across the entire country. The benefits of offshore wind thus expand far beyond the U.S. coastline.

DIVERSIFYING THE CLEAN ENERGY MIX TO POWER A NET ZERO FUTURE

Scaling the offshore wind industry to provide 10-25% of total electricity generation in 2050 will require an ambitious, long-term policy agenda, robust industrial policy support, and large investments in the supply chain, infrastructure, and transmission systems. In order to achieve net zero targets, the U.S. will need to deploy new renewable energy capacity at nearly four times today's annual rate of deployment. But the benefits can be huge — development of the U.S. offshore wind industry would provide a highly productive, reliable clean energy resource needed to help achieve a 2050 economy-wide net zero target, alongside ambitious land-based renewable energy development.

TABLE OF CONTENTS

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GridLAB

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GridLab is an innovative non-profit that provides technical grid expertise to enhance policy decision-making and to ensure a rapid transition to a reliable, cost effective, and low carbon future.

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Energy Innovation is an energy and climate policy think tank that produces independent analysis to inform policymakers of all political affiliations in the world's largest emitting regions. Energy Innovation delivers objective, science-based research to policymakers and other decision-makers seeking to understand which policies are most effective to ensure a climate safe future for all.

INTRODUCTION

Global carbon emissions must be halved by 2030 to limit global warming to 1.5° Celsius and avoid the most catastrophic impacts of climate change (UN IPCC, 2023). Most existing studies, including the original report that launched the 2035 Report series in 2020, demonstrate that a combination of land-based wind, solar, and battery storage can cost-effectively decarbonize much of the U.S. power sector (Phadke et al., 2020). However, the path towards U.S. decarbonization will be unprecedented, requiring extensive annual deployments of clean energy, as well as significant policy reform.

The original 2035 Report: Plummeting Solar, Wind, and Battery Costs Can Accelerate our Clean Electricity Future (2035 Report 1.0) charted a feasible and cost-effective pathway to reach 90% clean electricity by 2035 (Phadke et al., 2020). The second 2035 Report: Plummeting Costs and Dramatic Improvements in Batteries Can Accelerate Our Clean Transportation Future (2035 Report 2.0) expanded on this analysis by modeling the increased demand from the electrification of the transportation sector (Phadke et al., 2021). This report builds on previous assessments, examining potential pathways to 90% clean electricity by 2035 and 95% clean electricity by 2050 and meeting increased load from the electrification of buildings, transportation, and industry, while deploying significant amounts of new offshore wind capacity. With a targeted commitment, offshore wind could support 10-25% of the nation's electricity demand by 2050.

2035 Report 3.0 looks beyond the original target of 90% clean electricity by 2035, with a more ambitious goal of achieving near-net zero carbon emissions economy-wide by 2050. This report focuses on how the rapid deployment of offshore wind can help achieve near- and long-term decarbonization targets, even as the technology to achieve the final 5%-10% of power sector decarbonization is rapidly evolving. The year 2035 is a critical inflection point on the nation's journey towards net zero emissions. The U.S. will need to continue to diversify the set of clean energy technologies to meet rising electricity demand, while simultaneously building out the grid and supporting industries to bring widespread, cost-effective power. Offshore wind is a powerful and scalable technology to help meet those needs.

Offshore wind's plummeting costs and marked performance improvements have led to the industry's rapid expansion worldwide and dramatically enhanced the prospects for near-term power sector decarbonization. Offshore wind costs are estimated to fall nearly 30% by 2035, to approximately $53/MWh (WETO, 2023). Reducing the cost of offshore wind in other countries has required a holistic approach, using government policies to provide long-term certainty to a nascent industry, while addressing transmission, port, vessel, and supply chain constraints.

Despite a federal commitment to achieve net zero emissions by 2050, the U.S. still lags behind the rest of the world in offshore wind ambition and deployment. The U.S. has a goal to deploy 30 GW of offshore wind by 2030, and has a current project pipeline of approximately 50 GW (ACP, 2023). This pipeline would likely meet less than 2% of the nation's electricity demand in 2050. As of 2022, cumulative installed global capacity of offshore wind reached more than 55 GW, with 709 GW of projects in the international pipeline (GEM, 2023). As offshore wind deployment and associated cost reductions continue, nations have recognized the need to increase the ambition of their offshore wind targets to leverage this promising technology and reap further economic benefits.

Leadership has been most pronounced in Europe and China (Figure 1). China installed 20 GW of offshore wind in the last two years (GWEC, 2023). The United Kingdom (U.K.), with annual electricity demand less than 10% that of the United States, has already installed 13 GW of offshore wind, which provides 13% of the nation's electricity generation. The U.K. plans to expand offshore wind from the current 13 GW to 50 GW by 2030, comprising more than 50% of total generation (National Grid ESO, 2023; ACP, 2023). Nine European nations including the U.K. recently announced a target to deploy 300 GW of offshore wind in the North Sea by 2050 (Henley, 2023). Achieving a similar scale in the U.S. would imply a national offshore wind target of at least 400-500 GW by 2050.

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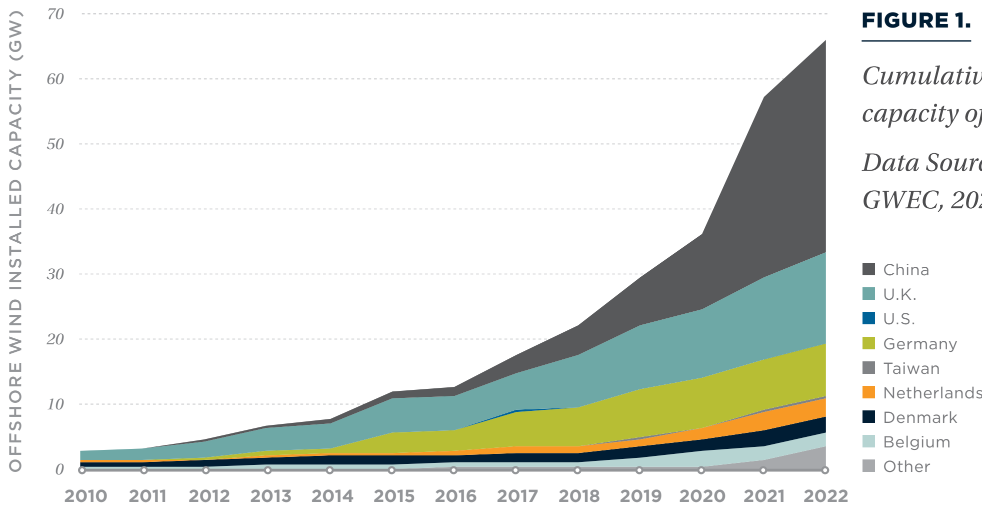


FIGURE 1.

Cumulative installed global capacity of offshore wind, 2022.

Data Sources: BNEF, 2022; GWEC, 2023.

Even though the United States has some of the strongest offshore wind resources in the world, the first two large-scale domestic offshore wind plants are only just entering into service in 2023. The extensive U.S. coastline and strong sea winds have the technical potential of nearly 4,000 GW of offshore wind capacity—approximately four times the amount of capacity of the entire U.S. power grid today. Select areas off the U.S. coastline offer enough wind resource to generate 1,000 GW of energy with capacity factors[1] greater than 50%. Some of the best wind resources in the country sit just off the coast of major population centers with significant electricity demand, including the Northeast corridor and California coast.

Similar to earlier forecasts for solar and land-based wind resources, experts' cost projections continue to prove conservative when compared with rapid real-world declines in cost. Levelized cost of electricity (LCOE) projections, such as those produced in the National Renewable Energy Laboratory's (NREL) Annual Technology Baseline (ATB), consistently need to be revised downward to match market behavior (Figure 2) (NREL, 2022). Experts forecast average U.S. offshore wind LCOE prices to fall to $53/MWh by 2035, below the average price of a new combined cycle natural gas plant and on par with existing solar and wind plants (DOE, 2023). Recognizing the ability to beat these forecasts, the Department of Energy has a "Floating Offshore Wind Shot" goal to deploy 10 GW of floating offshore wind by 2035 and reduce costs to $45/MWh (EERE, 2023).

1 Capacity factor is defined as the ratio of energy produced by a generator in a given period of time relative to the total amount of energy that the generator could have produced operating at full power during that time. It is a measure of how productive that particular generating technology is.

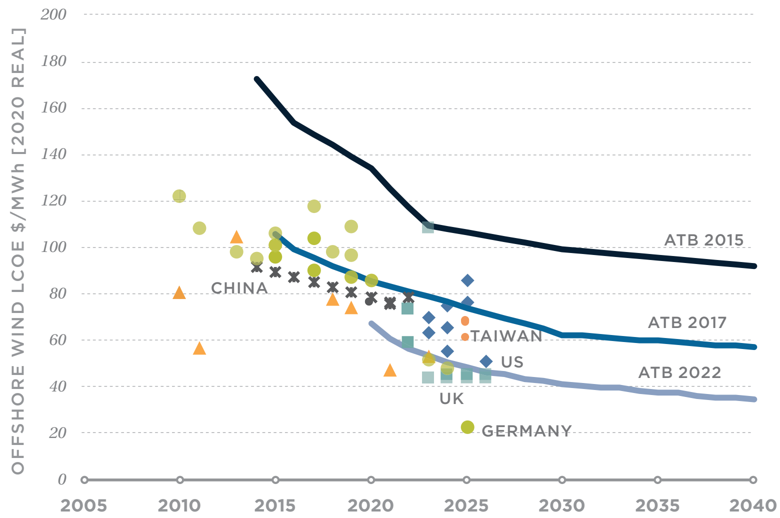


FIGURE 2.

NREL Annual Technology Baseline Advanced cost projections for years 2015, 2017, and 2022. Levelized cost of electricity for selected offshore wind projects in China, Taiwan, United States, United Kingdom, and Germany. All project costs are in $ 2020 real.

Data Source: BNEF, 2022.

Offshore wind levelized cost of electricity projections are detailed for the year in which each projection was made in the NREL ATB (NREL ATB 2015, 2017, 2022) using NREL ATB Advanced cost projections for Class 1 (Fixed Bottom) offshore wind resources. LCOE projections are illustrating the consistent downward revision of costs. The individual markers represent commercially operating offshore wind projects throughout the world, which consistently fall below projected LCOEs.

While the United States continues to make progress on national decarbonization, achieving net zero emissions, in which the nation emits no more carbon into the atmosphere than it removes, requires significantly ramping up clean energy production while electrifying other sectors of the economy, such as buildings, transportation, and industry. We forecast this solution will cause U.S. electricity demand to triple by 2050, requiring even greater reductions in the percentage of electricity produced from fossil fuels and sustained rapid deployment of clean energy technologies through 2050. This trajectory is critical to meet our national climate goals and limit the worst impacts of climate change.

Offshore wind can help meet this dramatic increase in demand, complementing existing land-based clean energy resources and providing abundant energy during critical peak periods. The race to deploy new clean energy resources is increasingly crowded and complex. In order to meet net zero targets, the nation must deploy renewable resources at five to six times the rate of deployment in 2022. Accelerating clean energy development on land and further expanding deployment to the water would help meet these ambitious goals and defray some of the land-use constraints facing a business-as-usual approach to reaching net zero. The U.S. Exclusive Economic Zone[2] (EEZ) is the largest in the world. The contiguous EEZ measured in this study comprises 2.7 million square kilometers, nearly one-third the size of the contiguous United States. With appropriate policy support, enhanced environmental screening and siting at scale, proactive and holistic transmission planning approaches, and robust support for supply chain and port expansion, this space can serve as a critical hub of new clean energy generation. By continuing to diversify the clean energy mix with cost-effective resources such as offshore wind, the nation increases the odds of meeting net zero ambitions equitably.

Going big on offshore wind would also provide economic benefits across the country. Employment analysis suggests that through robust supply chain development, an ambitious offshore wind deployment target could support nearly 390,000 new jobs nationwide in 2050. While there are significant supply chain hurdles to overcome, efforts to scale wind technology manufacturing now can help the U.S. establish the production, operational, distribution, and maintenance infrastructure required to meet clean energy targets—making it more likely to avert the most extreme catastrophes related to climate change.

After a brief description of methods, scenarios, and data in the following section, key findings of the 2035 Report 3.0 are summarized. The report's appendices provide details of the analyses and results.

A companion report from Energy Innovation, Policy Priorities to Ensure Offshore Wind Plays a Central Role in our Net-Zero Future, outlines key policy recommendations to support ambitious offshore wind goals and overcome deployment barriers (Energy Innovation, 2023). Another related report from Daymark Energy Advisors explores the potential of an offshore transmission backbone to facilitate reliability and cost reductions (Daymark Energy Advisors, 2023). A supporting report from Cambridge Econometrics, highlights the economic and employment benefits of large-scale offshore wind deployment (Hodge et al., 2023). One final report from UC Berkeley evaluates the supply chain, port, vessel, and investment requirements of a national offshore wind deployment strategy (Matos, Wooley, 2023).

2 200 nautical miles from the coast, excluding state waters.

SCENARIOS, DATA, AND METHODS

This report combines the latest renewable energy and transmission cost and performance data with state-of-the-art power systems modeling to demonstrate the technical and economic feasibility of achieving 90% carbon-free[3] ("clean") electricity by 2035 and 95% clean electricity by 2050 while expanding offshore wind capacity. While the Biden administration has a goal of achieving 100% clean electricity by 2035, each scenario in this report including the baseline scenario examines 90% clean electricity by 2035 and 95% in 2050. This modeling approach avoids the complexity of modeling fully decarbonized systems, instead, focusing on commercially viable technologies that can contribute significant near-term power systems emissions reductions.

While we do not allow the model to deploy new fossil fuel resources, the model can choose new green hydrogen fueled combustion turbines.[4] The model may also choose to deploy battery storage technology in durations of 2, 4, 6, 8, or 10 hours. Consistent with EPA's recent regulations on existing coal-fired power plants, we also force the model to retire all unabated coal capacity by 2035.

This analysis builds on the methods and results developed in the 2035 Report 1.0, once again demonstrating the technical and economic feasibility of the United States achieving 90% clean electricity by 2035 (Phadke et al., 2020). 2035 Report 3.0 goes beyond the scope of 2035 Report 1.0 to explore how targeted deployment of offshore wind can help cover dramatic demand increases from the electrification of transportation, industry, and buildings and meet near-net zero goals by 2050. Not only does this report look at a longer time horizon, it takes a more comprehensive look at net zero-aligned electricity demand growth while focusing on the potential contributions of offshore wind, a resource that was not included in either the 2035 Report 1.0 or 2.0 analysis.

3 Generation from any resource that does not produce direct carbon dioxide emissions is considered "clean" in this analysis, including generation from land-based and offshore wind, solar, geothermal, nuclear, biomass, and hydropower.

4 In this study, renewable combustion turbines are combustion turbines that use green hydrogen as fuel to power a turbine and produce electricity.

OFFSHORE WIND POTENTIAL AND PROFILES

We identified and created resource profiles for potential suitable offshore wind plant sites along the U.S. coastline, including the Great Lakes, based on data and tools from NREL, the National Aeronautics and Space Administration (NASA), and the International Energy Agency (IEA). We relied on methods detailed in NREL's resource potential dataset to identify approximately 10,000 suitable offshore wind plant sites across the U.S. at 11.5 km spatial resolution (Lopez et al., 2022). To begin, we established the total ocean area within the U.S. Exclusive Economic Zone (200 nautical miles from the coast, excluding state waters), including the Great Lakes. We then removed any areas with water depths greater than 1,300 meters, conservation areas, marine protected areas, shipping lanes, danger zones, submarine cables, military areas, shipwrecks, ocean disposal sites, oil/gas pipelines, platforms, and other existing infrastructure. While this represents a robust modeling approach, in reality, additional ocean uses arise during the leasing, site identification, and environmental review processes that will further restrict the total available area for offshore wind development.

To develop hourly wind generation profiles, we used meteorological data such as hourly wind speeds, wind direction, pressure, and temperature from NASA's MERRA-2 reanalysis product and then used the Global Wind Atlas dataset to downscale the wind speeds at each site (Global Wind Atlas, 2022; NASA, 2023). We then used NREL's System Advisor Model (SAM) to simulate offshore wind generation at each of these 10,000 sites (Blair et al., 2018). We used the power curve from International Energy Agency's (IEA) 15 MW offshore Reference Turbine, which has a rotor diameter of 240 meters and a hub height of 150 meters (Gaertner et al., 2020).[5]

We modeled hourly generation for a 600 MW wind farm consisting of 40 turbines of 15 MW each arranged in a rectangular shape with 8 rows and 5 columns. The SAM model takes as input wind speeds, wind direction, pressure, temperature, and turbine power curve, and outputs hourly wind generation for a farm considering the impact of wake effects using the Simple Wake Model in SAM and 10% electrical losses. The Simple Wake Model uses the wind speed deficit factor to estimate the reduction in wind speed at a downwind turbine due to the wake of an upwind turbine. Please refer to the appendix for more details.

5 We validated average wind speeds developed for this analysis with NREL's latest wind speed dataset for three call areas in California and found that our wind speed estimates match closely with those of NREL's (Optis et al., 2020). Although we have used industry-standard weather datasets that are widely used, additional work is needed to correct any systemic weather and terrain biases.

The offshore wind potential and profile analysis utilizes the same methodology as NREL, updated to reflect commercially available technology and improved performance standards. Our updated analysis uses a larger turbine deployed at higher hub heights, reflective of the standard technology in use today. Newer, higher performing turbines deployed at higher hub heights have the effect of increasing average capacity factors and thus increasing total energy generation.

POWER SECTOR ANALYSIS

We performed state-of-the-art power sector modeling to evaluate potential pathways for decarbonization using NREL's open-source, capacity-expansion ReEDS model and Energy Exemplar's PLEXOS modeling tool (NREL, 2023; Energy Exemplar).

We utilized publicly available generation and transmission datasets. Forecasts of offshore wind technology, renewable energy, and battery storage costs are based on NREL's 2022 ATB (NREL, 2022). ATB includes three forecasts for all technologies:

- A "Moderate" or mid-cost case.
- An "Advanced" or low-cost case that assumes more aggressive cost declines due to technology advancement and learning.
- A "Conservative" or high-cost case that assumes slower cost declines.

The offshore wind profiles and capacity factors developed using the IEA 15 MW Reference Turbine at a hub height of 150 meters were then applied to the ReEDS model. A detailed description of modeling tools and assumptions can be found in the appendix.

GRID DEPENDABILITY ASSESSMENT

Replicating the methodology from previous 2035 Reports, we analyzed the sensitivity of the High Ambition offshore wind scenario to periods of extremely low clean energy generation and/or high demand in order to ensure that the system can dependably meet demand (Phadke et al., 2020; Phadke et al., 2021). The power systems analysis considers the performance of each of the more than 20,000 individual generating units on the U.S. power grid and all major transmission interfaces.

We utilized the PLEXOS production cost model to simulate hourly operation of the power system, a total of 60,000 hours over seven unique weather years.

In order to prove that the system is dependable — such that the generation supply is able to meet demand at all times, including periods of low renewable energy generation, high intermittency, and peak load — we modeled each hour while abiding to specific technical constraints, such as ramp rates, minimum generation requirements, and minimum reserve requirements.

The Grid Dependability Assessment only assesses the generation impacts of the High Ambition scenario, in order to demonstrate the dependability of a grid operating with extremely high levels of offshore wind and other renewable energy generation.

While this represents a technically rigorous approach to evaluating nationwide power systems performance, further detailed analysis is required to evaluate the impact of 95% clean generation on local reliability and resource adequacy. A full description of the power systems methodology is detailed in the Appendix.

KEY ASSUMPTIONS

The results of this analysis are largely driven by a number of key assumptions, including technology cost and performance, siting constraints, and clean energy policy. We considered three sets of future renewable energy costs, utilizing the NREL ATB cost projections (NREL, 2022).

We also utilized NREL's primary siting constraints to evaluate sensitivity to the availability of land for renewable energy deployment (Lopez et al., 2021). We evaluated two sensitivities developed by NREL on the siting of land-based renewable energy, Reference and Limited. The Limited case has more stringent siting considerations, such as higher setbacks from buildings and civil infrastructure. For example, land-based wind resources in the Limited siting sensitivity require setbacks of three times the turbine tip height, cannot develop within a radar line of the turbine (from military or weather radar), and cannot develop on any federal lands. In effect, the Limited siting sensitivity significantly reduces the area available for land-based renewable energy development, particularly wind, while solar is less affected due to the abundance of suitable sites.

The offshore transmission network was modeled with two sensitivities, which are further detailed in Key Findings:

- *Single plant approach:* each individual 600 MW offshore wind plant is connected directly to the onshore transmission network.
- *Clustered approach:* a single line connects multiple 600 MW offshore wind plants directly to the onshore transmission network.

A full description of the transmission analysis is detailed in the Key Findings section, the Appendix, and a supporting report from Daymark Energy Advisors.

We assume the U.S. reaches near-net zero emissions economy-wide by 2050. This implies aggressive electrification of the transportation, buildings, and industrial sectors, as well as a rapid expansion of green hydrogen production for use in industry (Figure 3). We utilized:

- The *2035 Report 2.0* assessment of additional electricity demand from transportation electrification (Phadke et al., 2022).
- A combination of other tools and sources, such as Energy Innovation's Energy Policy Simulator, the Princeton Net-Zero America Study, and NREL's Electrification Futures Study to assess the electrification demand from industries and buildings for near net-zero emissions (Orvis et al., 2022; Larson et al., 2021; and Murphy et al., 2021).
- The Energy Policy Simulator and NREL's *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035* (Denholm et al., 2022) to estimate the hydrogen demand from industries.

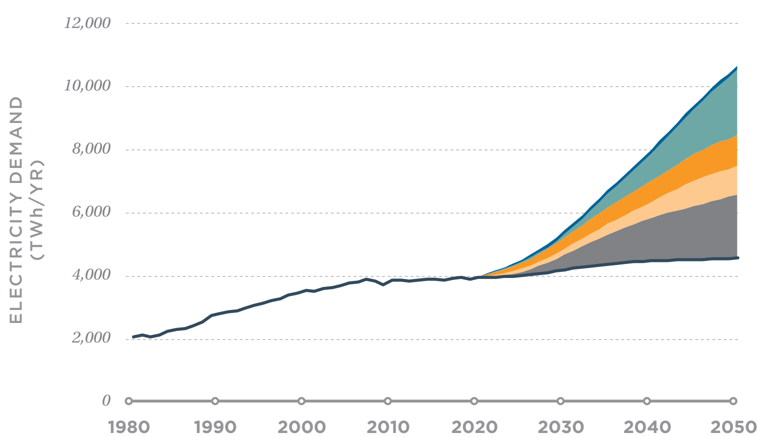


FIGURE 3.

Historical and projected electricity demand, with projected load growth in the transportation, building, industrial, and hydrogen sectors.

The growth in electricity demand in the transportation and building sectors aligns with 100% electrification of those sectors. In the transportation sector, our demand projection is representative of a future in which 100% of new vehicle sales are electric by 2035, closely aligned to those assumptions developed in 2035 Report 2.0 (Phadke et al., 2022). In the buildings sector, we assume 100% of new appliance and equipment sales to be electric by 2030, coupled with aggressive end-use efficiency improvements. In the industrial sector, our demand projection is representative of a future in which 100% of low- and medium-heat applications are electrified by 2050. 100% of the steel and ammonia manufacturing, as well as other high heat applications, utilize green hydrogen as a fuel and heat source by 2050.

This report explicitly examines a pathway towards near-net zero carbon emissions economy-wide by 2050, ultimately achieving 95-97% carbon reductions by 2050 relative to 2005 levels. We do not require the model to meet 100% net zero emissions, as that would likely require significant carbon capture and sequestration technologies, which is beyond the scope of this analysis.

SCENARIO DESIGN

We used these data and methods to analyze one baseline scenario and a range of offshore wind deployment scenarios. We analyzed the robustness of these assumptions across various sensitivities, resulting in a wide range of power sector outcomes. Table 1 below details the core offshore wind targets analyzed in this report, while Table 2 describes the main sensitivities applied in the model. The sensitivities are explained in more detail below and in the Appendix.

TABLE 1.

Key offshore wind targets analyzed in this report.

OFFSHORE WIND POLICY SCENARIOS	OFFSHORE WIND TARGETS	OFFSHORE WIND GENERATION (APPROXIMATE % OF TOTAL ELECTRICITY GENERATION IN 2050)
Business as Usual (Baseline)	40 GW by 2035 67 GW by 2050	2%
Low Ambition	100 GW by 2035 250 GW by 2050	10%
Medium Ambition	100 GW by 2035 500 GW by 2035	20%
High Ambition	100 GW by 2035 750 GW by 2050	25%

TABLE 2.

Key sensitivities analyzed in this report, for every combination of the following parameters (24 cases assessed for each offshore wind target, meaning a total of 96 model runs).

TECHNOLOGY COSTS	LAND-BASED RENEWABLE ENERGY AVAILABILITY	CLEAN ELECTRICITY POLICY	OFFSHORE TRANSMISSION INTERCONNECTION LAYOUT
ATB Advanced	Limited	90% by 2035 95% by 2050	Single Plant
ATB Moderate	Reference	Business As Usual	Clustered
ATB Conservative			

The offshore wind deployment scenarios all utilize the same set of core assumptions and technology costs. We compare the offshore wind deployment scenarios to one Baseline scenario.

- **Current Decarbonization Policy (Baseline Scenario):** Assumes current federal and state clean energy targets, existing technology performance and trends, and requires 90% clean electricity by 2035 and 95% clean electricity by 2050. Assumes a pathway towards near-net zero carbon emissions economy-wide by 2050.
- **Offshore Wind Policy Scenarios:** Requires 90% clean electricity by 2035 and 95% clean electricity by 2050, accompanied by 100 GW of offshore wind by 2035 and various levels of offshore wind deployment by 2050, comprising between 10-25% of total generation. Assumes a pathway towards near-net zero carbon emissions economy-wide by 2050.

TABLE 3.

Core scenarios discussed in this report.

	CURRENT DECARBONIZATION POLICY (BASELINE SCENARIO)	OFFSHORE WIND POLICY SCENARIOS
Policy Assumptions	• Includes state, regional, and federal policies as of 2022 • Incentives from the Inflation Reduction Act and other energy tax credits	
Clean Electricity Mix Targets	• Pathway towards near-net zero carbon emissions economy-wide by 2050 • 90% by 2035, nationwide • 95% by 2050, nationwide	
Offshore Wind Capacity Targets	• Current federal and state offshore wind targets	• 100 GW of offshore wind by 2035 • 250, 500, and 750 GW of offshore wind by 2050
Scope of Electrification	Buildings, transportation, and industrial sectors, including green hydrogen production	
Cost Projection Basis	ATB Moderate	
Land-Based Renewable Availability	Limited	
Fossil Fuel Power Plant Status	• All existing coal retired by 2035 • No new fossil gas additions after 2023 except ones that are currently under construction	

We designed the Offshore Wind Policy scenarios with international targets in mind. North Sea countries, the European Union (EU) as a whole, China, South Korea, and Southeast Asia have committed significantly to offshore wind at a scale well beyond current U.S. commitments (Figure 4). This signals room for increased U.S. ambition, and foreshadows further technological improvements and cost reductions enjoyed by more mature renewable technologies such as solar and onshore wind with similar characteristics. Though our scenarios do not explore the relationship between scale and endogenous learning, the scientific literature increasingly supports the proposition that greater deployment leads to faster cost declines of renewable technologies that have demonstrated they are on a learning curve (Way et al., 2022).

The Global Ambition to Increase Offshore Wind Generation

Around the globe, offshore wind development is increasingly viewed as a key decarbonization tool, and the industry is expanding rapidly. While the targets analyzed in this report are ambitious, international clean energy development offers insight into the global clean energy revolution underway that the U.S. is poised to act on. Globally, the pipeline for new offshore wind capacity continues to rise and now stands at over 700 GW of announced capacity (GEM, 2023).

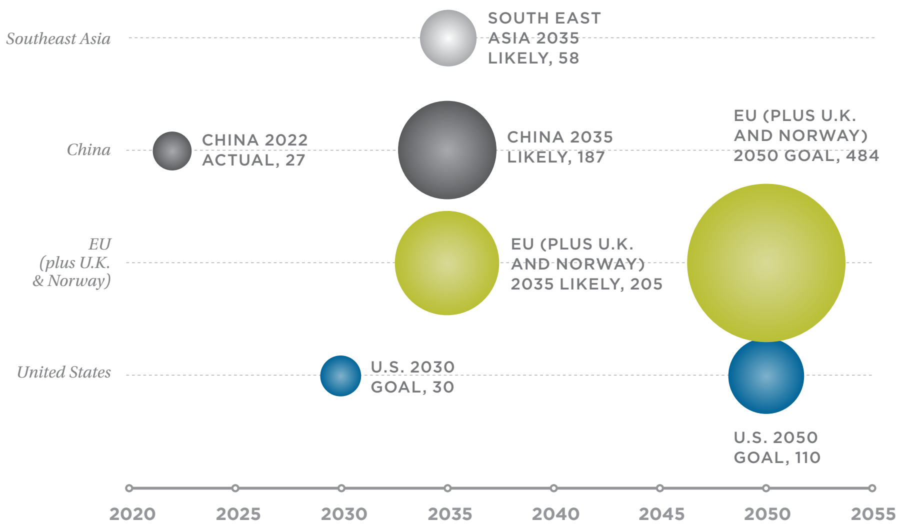


FIGURE 4.

Likely offshore wind capacity targets in China, the European Union plus Norway and the United Kingdom, and the United States, 2020-2050.

Data Source: BNEF, 2023.

Cumulative installed offshore wind capacity now stands at over 55 GW, following a record-setting 2021 in which nations around the globe installed 21 GW of offshore wind (GEM, 2023; GWEC, 2023). Numerous countries have consistently upped the ambition of their installation targets, recognizing the necessity of new offshore wind capacity. The European Union previously announced targets to deploy 110 GW of offshore wind by 2030, and at least 350 GW by 2050 (European Commission, 2023). Such a target far surpasses the Biden Administration's goal to deploy 30 GW of offshore wind by 2030 and 110 GW by 2050. At this rate, offshore wind would provide approximately 5% of the nation's 2050 electricity demand. Total EU electricity demand is approximately 66% of the U.S. total electricity demand, suggesting that the EU plans to meet a significantly higher share of total generation from offshore wind than the U.S. currently plans to.

Nine North Sea nations recently announced a plan to go beyond the EU targets, hoping to deploy 120 GW of offshore wind by 2030 and 300 GW by 2050 in the North Sea (Henley, 2023). The nine nations, whose combined electricity demand represents just 40% of current U.S. electricity demand, will need to deploy upwards of 20 GW per year to meet the 2050 target. While offshore wind proliferation in Europe started long before the United States' entrance into the industry, the scale and speed of their targets warrants a significant point of comparison.

China remains a global leader in installed renewable energy capacity. In 2022, China installed approximately 29 new offshore wind plants. At the same time, other nations are joining the burgeoning industry. Vietnam, Japan, the U.K., South Korea, Italy, France, Spain, and Germany all completed projects in 2022 (Buljan, 2023).

KEY FINDINGS

This section highlights our analysis' top findings, which indicate how critical offshore wind will be in meeting U.S. commitments to reach net zero greenhouse gas emissions by 2050. We analyze the impacts of offshore wind providing an increasing amount of total energy generation to the U.S. power mix in 2050 compared to a Baseline scenario. In the Baseline scenario, 67 GW of offshore wind contributes approximately 2% of generation as a share of total energy generation in 2050. Our three scenarios — Low Ambition, Medium Ambition, and High Ambition — show the electricity system impacts of offshore wind growing to provide 10-25% of total generation, allowing a more robust examination of the tradeoffs between these approaches as policymakers attempt to balance ambition and feasibility.

- The U.S. has some of the highest offshore wind speeds and potential capacity in the world, amounting to over 4,000 GW of technical potential. 1,000 GW of potential offshore wind capacity along the East Coast, Gulf of Mexico, West Coast, and Great Lakes has capacity factors over 50%.
- Offshore wind can be integrated into the U.S. power system and provide 10-25% of total electricity generation in the U.S. power system in 2050 without substantially impacting wholesale electricity costs. Wholesale electricity costs are just 0.25% higher in the High Ambition scenario than Baseline in 2050, while costs in the Low and Medium Ambition scenarios are lower relative to Baseline.
- The transition to 100% clean electricity and a net zero economy will require unprecedented amounts of new clean energy capacity. We find that offshore wind can strengthen and de-risk the U.S. pathway to power sector decarbonization in a high electrification scenario. The Mid Ambition scenario would require annual deployments of approximately 100 GW of land-based wind and solar, and 27 GW of offshore wind between 2035-2050. The additional offshore wind capacity reduces the total amount of capacity installed on the U.S. power system by nearly 500 GW relative to Baseline.
- Researchers have identified a pathway to developing supply chains that adequately support the Biden Administration's 30 GW by 2030

target, and all Offshore Wind Policy scenarios will require coordinated and deliberate industrial policy support beyond 2030 to increase domestic manufacturing, develop specialized port facilities and ships, and enhance local employment opportunities. Our analysis suggests that in order to support an offshore wind industry that provides 20% of the nation's electricity demands, cumulative investment in the supply chain would need to exceed at least $260 billion through 2045.

- High-quality wind resources across the nation expand the available deployment and associated economic opportunities of offshore wind. Offshore wind reduces the burden of infrastructure development on land, and shifts it offshore, diversifying the risk of infrastructure development to a wider area. As offshore wind deployment increases, the area directly impacted by renewable energy infrastructure decreases relative to the Baseline scenario. Because of the high power density of offshore wind resources, the U.S. could generate more clean power on a smaller footprint on water.
- The transition to a net zero economy will require doubling existing transmission infrastructure, amounting to at least $700 billion in new transmission investment by 2050. However, a clustered transmission approach, which allows for greater aggregation of offshore wind production into fewer collection points, could reduce offshore transmission costs by 35% relative to a business-as-usual approach. Offshore wind provides an opportunity to reimagine the transmission planning process and avoid the bottlenecks that have plagued land-based renewable energy deployment.
- Achieving near-net zero emissions by 2050 through electrification of the economy will result in the annual demand for electricity to soar to at least 10,700 TWh, with daily peak demand reaching over 2,100 GW in the winter. Offshore wind has a complementary generation profile to that of solar and land-based wind, and is well-suited to meet electrification demand. By complementing the generation profiles of existing clean energy technologies, offshore wind can help form a system equipped to more reliably match electricity demand patterns and diversify the electricity mix.
- When isolating the impacts of just offshore wind development, the High Ambition offshore wind policy scenario could support approximately 390,000 jobs across the economy. A scenario in which a greater percentage of goods and materials are sourced domestically — a policy goal of the Inflation Reduction Act — leads to additional job creation, while expanding employment and economic benefits across the entire country. The benefits of offshore wind thus expand far beyond the U.S. coastline.

THE UNITED STATES HAS HIGH-QUALITY, ABUNDANT OFFSHORE WIND RESOURCES

The U.S. has some of the highest offshore wind speeds and potential capacity in the world. The offshore wind potential along the Eastern Seaboard, Gulf of Mexico, Great Lakes region, and the Pacific coast totals more than 4,000 GW (Figure 5). Over 1,000 GW of that offshore wind resource offers capacity factors greater than 50% (Figure 6).

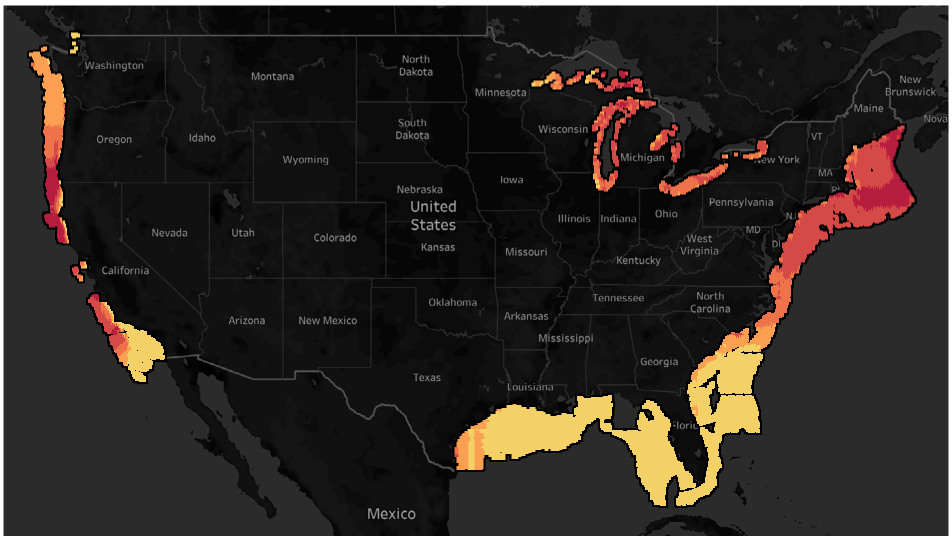


FIGURE 5.

Offshore wind technical resource potential and capacity factors, averaged over seven weather years (2007-2013).

CAPACITY FACTOR

35% 60%

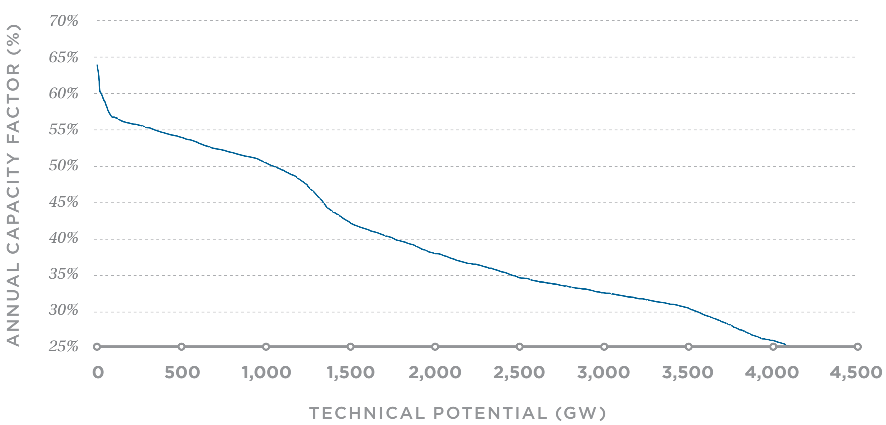


FIGURE 6.

Offshore wind capacity factor supply curve, averaged over seven weather years.

Offshore wind generation can help meet the rising energy demands of a highly electrified net zero economy, and all coastal regions of the country have quality offshore resources. The Northeast, West Coast, and Great Lakes regions' offshore wind monthly capacity factors typically average around 50%, while the Southeast and Gulf Coast have capacity factors of at least 35%. 65% of total U.S. electricity demand today comes from coastal or Great Lakes states, and can be served directly by offshore wind.

Offshore wind has a complementary generation profile to that of solar and land-based wind. Nationwide, offshore wind generation peaks in the evening, ramping up as solar generation begins to fall. Offshore wind generation is greatest in the summer on the West Coast, providing capacity needed to cover peak air conditioning loads. On the East Coast, the greatest amount of offshore wind is generated in the winter, coinciding with peak periods of heating demand, which is expected to increase as buildings and industry electrify heating (Figure 7). Offshore wind's high levels of evening generation also reduce the need for energy storage.

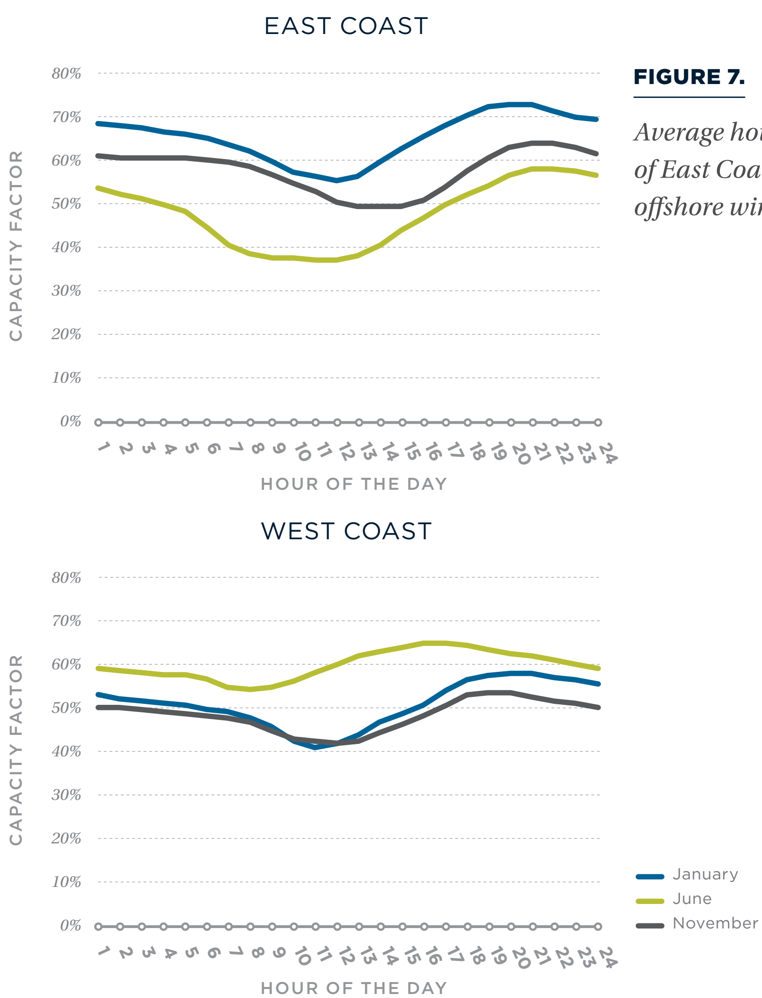


FIGURE 7.

Average hourly capacity factors of East Coast and West Coast offshore wind.

OFFSHORE WIND CAN BE INTEGRATED INTO THE U.S. POWER GRID WITHOUT IMPACTING WHOLESALE ELECTRICITY COSTS RELATIVE TO BASELINE

Wholesale electricity costs (generation costs plus new transmission) in the Offshore Wind Policy scenarios are comparable to Baseline throughout the study period. In the High Ambition scenario, in which offshore wind provides nearly 25% of total energy generation in 2050, wholesale electricity costs in 2035 are just 2.2% higher relative to Baseline, and just 0.25% higher than Baseline in 2050 (Figure 8). A coordinated transmission approach could further reduce the cost difference between the Baseline and Offshore Wind Policy scenarios.

Increasing the share of generation from offshore wind modestly impacts wholesale electricity costs throughout the study period. As offshore wind deployment increases, total wholesale electricity costs fall relative to the Baseline scenario, until offshore wind generation reaches approximately 20% of total energy generation. In the Low and Medium Ambition scenarios, wholesale electricity costs are approximately 2% and 3% cheaper than Baseline in 2050, respectively. In the interim years, costs in the Offshore Wind Policy scenarios are slightly higher than Baseline costs. In 2040, the wholesale electricity costs in the Low and Medium Ambition scenarios are 0.4% and 2.6% more expensive than Baseline, respectively.

In order to achieve a 95% clean electricity share, wholesale electricity costs rise modestly relative to today's electricity costs, but the rate of increase is comparable across both scenarios. The Inflation Reduction Act (IRA) offers significant tax incentives to support the deployment of new renewable and battery storage resources, including offshore wind, and helps mitigate any significant cost increases. In all cases including Baseline, wholesale electricity costs are approximately 13% higher in 2050 than today.

In all scenarios, electricity demand rises significantly, and with it, an accompanying increase in new generation capacity and new transmission is required. Despite offshore wind having higher capital costs than land-based wind and solar, offshore wind's high average capacity factor means less overall renewable capacity is required to meet load in the Offshore Wind Policy scenarios.

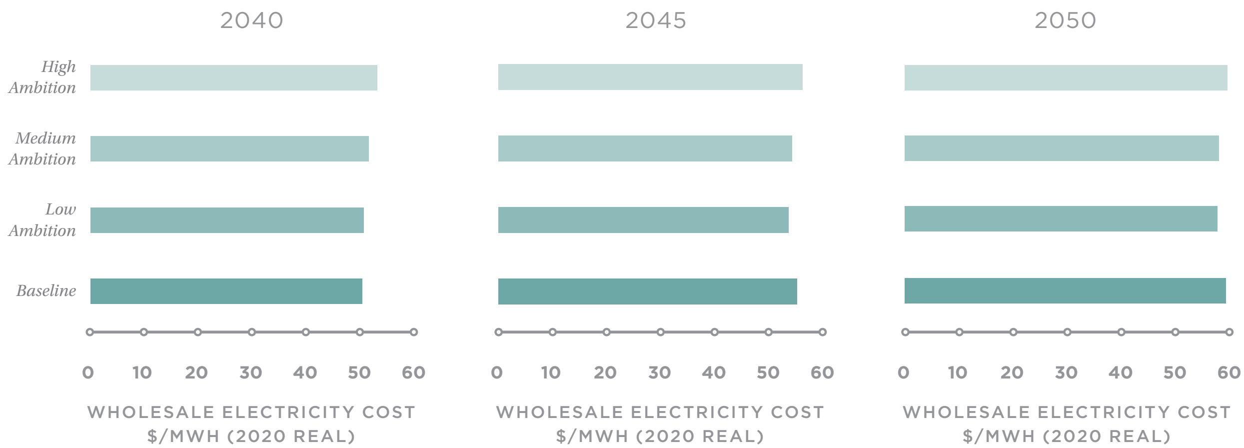


FIGURE 8.

Wholesale electricity costs ($/MWh) (generation plus new transmission) in Baseline and Offshore Wind Policy scenarios using NREL ATB Moderate costs, 2040-2050.

We applied sensitivities to evaluate how technology cost impacts overall total system costs. Figure 9 displays wholesale costs across all technology cost sensitivities. Even at the high deployment targets envisioned in the High Ambition scenario, wholesale electricity cost impacts remain modest. When utilizing ATB Advanced (low) technology costs, 2035 and 2050 electricity costs are both lower than those found in today's market. Future improvements in wind turbine performance and supply chain efficiency could lower capital costs, increase capacity factors, and deliver even more accelerated cost declines. For example, the ATB Advanced forecast utilizes an 18 MW turbine prototype, and assumes capital and operating expenditure reductions due to increased economies of scale, lower fabrication costs, and improved capacity factors (NREL, 2022). Future analysis could evaluate potential barriers to achieving cost reductions or improved performance such as supply chain constraints or macroeconomic impacts. There is also a need to more robustly examine endogenous learning through deployment and the impact on overall technology cost trends.

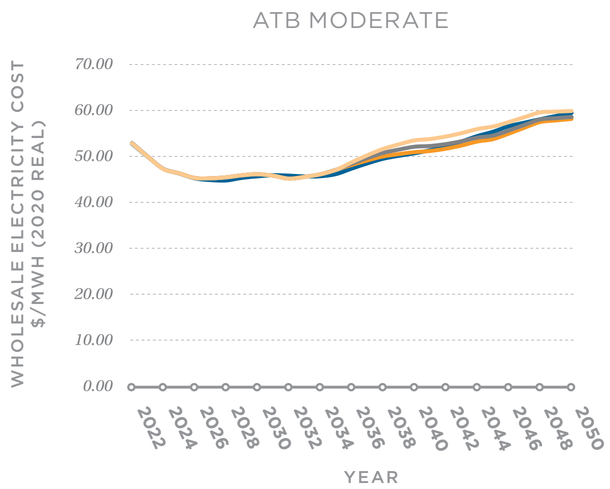
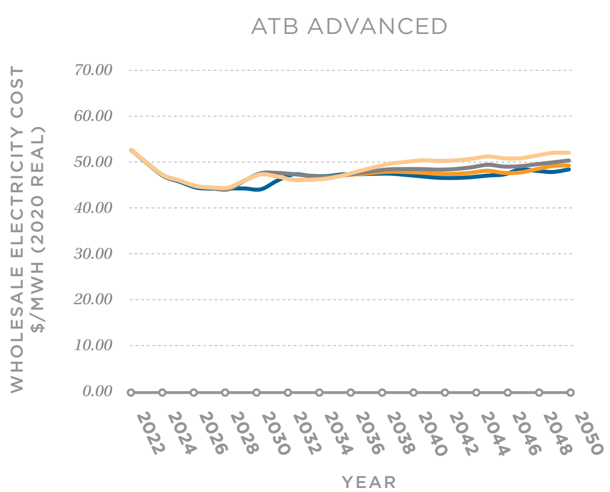
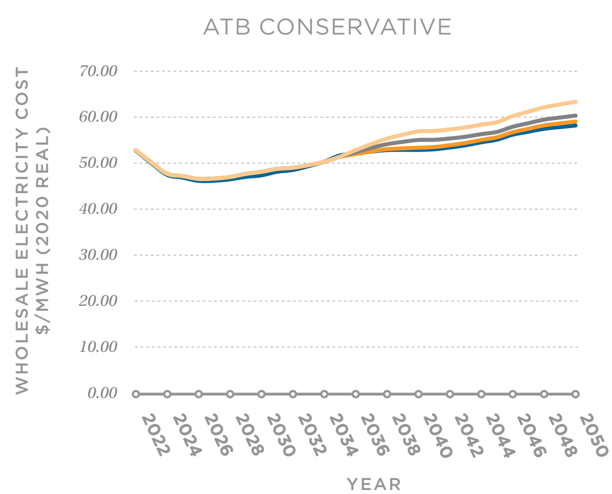


FIGURE 9.

Wholesale electricity costs ($/MWh) (generation plus new transmission) in Baseline and Offshore Wind Policy scenarios utilizing ATB Advanced, Moderate, and Conservative cost projections, 2023-2050.

High Ambition
Medium Ambition
Low Ambition
Baseline





OFFSHORE WIND COMPLEMENTS LAND-BASED RENEWABLES TO MEET INCREASED ELECTRICITY DEMAND IN A NET ZERO ECONOMY

To achieve net zero carbon emissions economy-wide requires elimination of fossil fuels and a national transition to electric vehicles, heat pumps, and other electric technologies in the industrial sector. The electricity needed to power all of this new technology, plus a growing U.S. economy, is expected to almost triple demand, from about 4,000 terawatt-hours (TWh) in 2020 to 6,700 TWh in 2035 and 10,700 TWh by 2050 (Figure 10).[6] While electricity demand grew on average 2.6% each year between 1975 and 2005, our analysis projects that the shift to an electrified economy will result in an average annual 3.3% increase in electricity consumption from 2023 to 2050.

6 This report examines a pathway towards near-net zero carbon emissions economy-wide by 2050, achieving 95-97% carbon reductions by 2050 relative to 2005 levels. We do not require the model to meet 100% net zero emissions, as that would likely require additional carbon capture and sequestration methods, which is beyond the scope of this analysis.

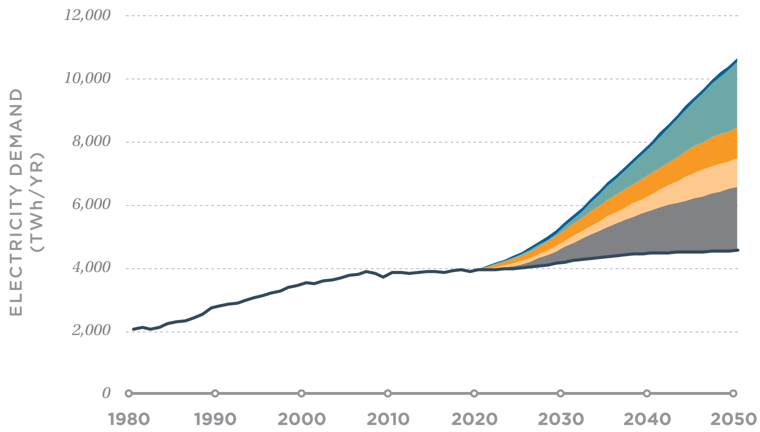


FIGURE 10.

Historical and projected electricity demand, with projected load growth in the transportation, building, industrial, hydrogen, and other sectors.

Today's electric grid comprises more than 1,000 GW of installed capacity. A combination of fossil fuels provide about 60% of total generation, while clean energy resources including nuclear, hydropower, biomass, geothermal, wind, and solar provide the rest. In order for the U.S. to grow that share of clean electricity to 90-95% by 2050 while electricity demand triples, installed capacity will likely grow at least fourfold, mostly via low-cost renewable generation.

Deploying that amount of infrastructure will be no easy task, raising the importance of relying on a diversity of resources, including offshore wind. This analysis suggests offshore wind could provide 10-25% of total generation in a near-net zero economy. Recently, the U.S. has deployed renewable resources at a record setting pace, including 28 GW in 2021, 18.5 GW in 2022, and an expected 35 GW of wind and solar in 2023 (EIA 860, 2023; EIA Today, 2023). Nevertheless, the nation will have to significantly increase annual installations of clean energy resources and accelerate deployment timelines in order to achieve net zero emissions. An accompanying scale-up of offshore wind capacity would bolster and complement renewable deployment trends on land and bring the U.S. closer to meeting its annual clean electricity needs.

By 2050, the Baseline scenario deploys 3,400 GW of new land-based wind and solar resources, plus 1,500 GW of new battery storage and 1,300 GW of hydrogen CTs, but only 67 GW of offshore wind.[7] Deploying 3,400 GW of land-based renewables by 2050 would require 127 GW of new capacity to be installed each year, four times the installations expected in 2023, and nearly five times the current record from 2021 (Figure 11).

7 Offshore wind deployments in the Baseline scenario are largely a result of state legislative procurement targets. For example, New York has a target to produce 9 GW of offshore wind by 2035, which is enforced in the model. The favorable economics of land-based wind and solar makes offshore wind slightly more expensive today, and so only modest amounts beyond procurement targets are deployed.

In contrast, we examine multiple Offshore Wind Policy scenarios that deploy increasing amounts of offshore wind. Our model does not endogenously build significant offshore wind capacity as part of the cost-optimum, reflecting the reality that additional policies will be needed to support scaling the offshore wind industry, explored in the companion policy report from Energy Innovation (Energy Innovation, 2023). The Offshore Wind Policy scenarios examine pathways to all clean energy technologies increasing their share of total energy generation, while evaluating offshore wind's specific contribution to that increase. In all policy scenarios, as fossil generation falls, offshore wind generation rises to meet 10-25% of total generation.

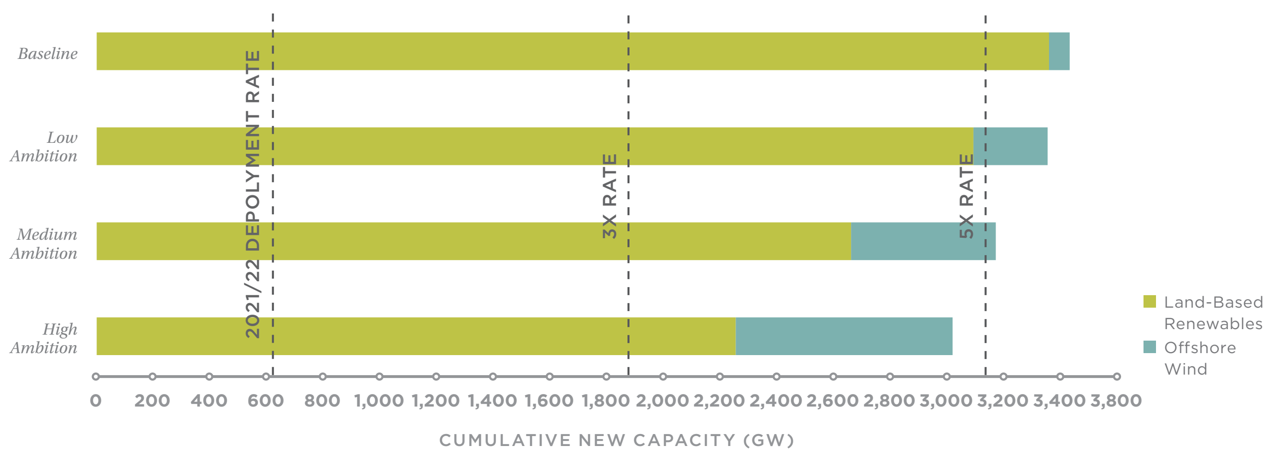


FIGURE 11.

Cumulative installed capacity of offshore wind compared to land-based wind and solar in the Baseline and Offshore Wind Policy scenarios, 2050.

In 2021, the United States deployed approximately 28 GW of new wind and solar resources, and 18.5 GW in 2022 (EIA 860, 2023). The bars on the chart represent a cumulative installation rate in 2050 of approximately 23 GW/year (the average of 2021 and 2022 installations), as well as three and five times that rate. In order for the U.S. to achieve near-net zero emissions by 2050, the nation will have to install land-based renewable energy at roughly three to six times the average deployment rate of 2021-2022 (5.5 times to reach the cumulative installed capacity of renewables in the Baseline scenario, but just 3.5 times to reach the cumulative installed capacity in the High Ambition scenario).

The Offshore Wind Policy scenarios require ambitious deployments of all clean energy resources to meet rising electricity demand. The Mid Ambition scenario deploys 500 GW of offshore wind by 2050, in addition to 600 GW of land-based wind, 2,000 GW of solar, and 1,200 GW of battery storage (Figure 13). In this scenario in 2050, offshore wind comprises 20% of total annual generation, while land-based wind and solar contribute approximately 20% and 45% of annual generation, respectively. The additional clean energy generation from offshore wind reduces the need for land-based wind and solar resources by 25% (700 GW) and battery storage capacity by 15% (200 GW) compared to the Baseline scenario. Coupled with existing gas, hydropower, and nuclear, as well as new green hydrogen fueled combustion turbines, clean generation is sufficient to dependably meet high electrification demand with 95% carbon-free electricity in 2050. In all scenarios, renewable energy technologies would contribute nearly 85% of total annual generation needs, accompanied by existing nuclear and hydropower, and new hydrogen CTs (Figure 12, Figure 14).

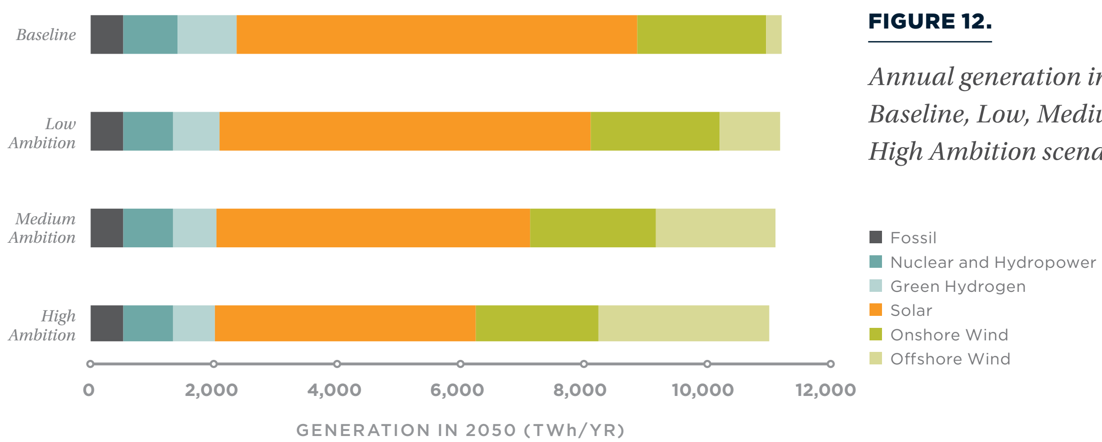


FIGURE 12.

Annual generation in the Baseline, Low, Medium, and High Ambition scenarios, 2050.

In order to reach the offshore wind deployment targets envisioned in this report, the United States would need to add an average 8 GW of new offshore wind per year between 2023 and 2035, and between 10-40 GW per year between 2035 and 2050. In *2035 Report 1.0 and 2.0*, we demonstrated the feasibility of scaling land-based renewables to meet annual deployment goals without the addition of offshore wind, which amounted to 70-110 GW of new land-based wind and solar per year, depending on electrification trends. This report considers a similar land-based renewable deployment target, while adding ambitious deployments of offshore wind. For example, the Baseline scenario requires annual renewable deployments of 127 GW per year, nearly five times the rate of 2021's record renewables deployment. As offshore wind capacity ramps up across scenarios, land-based renewable capacity falls slightly. The Mid Ambition scenario requires land-based renewable installations to proceed at closer to four times the 2021 deployment rate as offshore wind deployments increase from 8 GW per year in the 2020s, to 27 GW per year between 2035-2050.

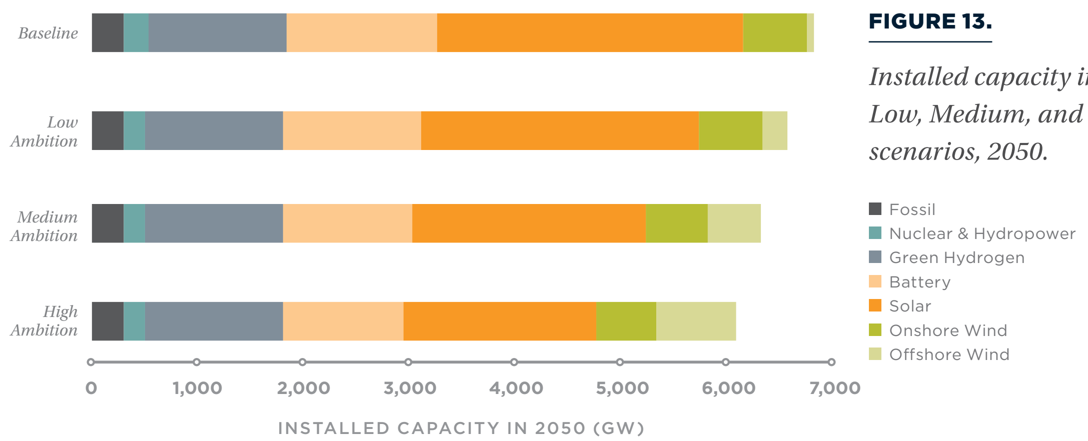


FIGURE 13.

Installed capacity in the Baseline, Low, Medium, and High Ambition scenarios, 2050.

2035 | The Pathway to Net Zero

The year 2035 represents a significant inflection point in the nation's decarbonization efforts. The Biden Administration has a target to achieve 100% clean electricity by 2035, which would help meet the nation's commitment to reduce economy-wide greenhouse gas emissions 50-52% by 2030 relative to 2005. The Biden Administration also has a target to deploy 30 GW of offshore wind by 2030. This report specifically examines achieving 90% clean electricity by 2035. While we recognize the necessity of achieving 100%, numerous other studies examine pathways to reach this target, often relying on new technologies to achieve the final 10% of decarbonization, such as hydrogen and carbon capture. Our analysis suggests the nation can achieve significant power sector decarbonization with technologies that are commercially viable today such as land-based wind, solar, battery storage, and now offshore wind. We focus this study on those technologies' contribution to clean energy generation, while avoiding the complexity and uncertainty involved in modeling the final 5-10% of power sector decarbonization.

This analysis requires the model to deploy 100 GW of offshore wind by 2035, such that offshore wind supplies approximately 5% of annual generation — a particularly challenging task that will require average annual deployments of approximately 8 GW per year. While difficult to achieve based on today's leasing and permitting processes, supply chain infrastructure, ports, and vessel capacity, scaling the industry over the next 12 years to target this goal is critical to ensuring that offshore wind becomes a substantial clean energy contributor by 2050. At the same time, the U.S. will need to be deploying at least 100 GW of land-based wind and solar each year. While challenges abound, the appetite for development persists. According to Lawrence Berkeley National Lab, there are over 110 GW of proposed offshore wind capacity in U.S. interconnection queues today (Rand et al., 2023).

The scale of new clean energy deployments under all scenarios is unprecedented, and will require coordinated policy support to ensure that manufacturing facilities and clean energy projects, including new transmission capacity, are permitted, financed, and constructed in a timely manner with adequate public consultation. Relying on the high levels of offshore wind reflected in our scenarios is not a silver bullet. However, new offshore wind capacity helps to diversify the energy mix, reduce the risk of missing our climate goals, and reflects a more balanced approach to the energy transition using proven technologies, even while recognizing the challenges of scaling the industry. The supporting report from Energy Innovation outlines numerous opportunities to reduce policy barriers to deployment while supporting a just and equitable energy transition (Energy Innovation, 2023).

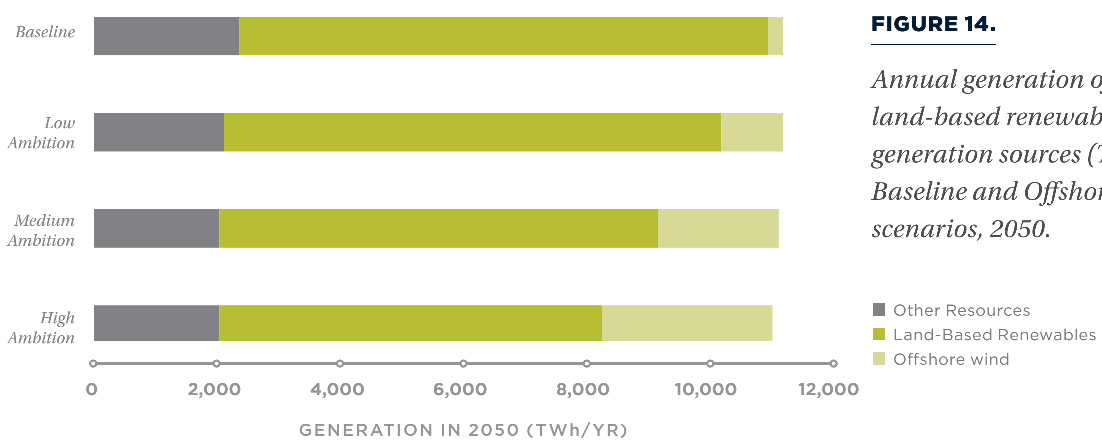


FIGURE 14.

Annual generation of offshore wind, land-based renewables, and other generation sources (TWh) in the Baseline and Offshore Wind Policy scenarios, 2050.

SCALING UP THE SUPPLY CHAIN WILL REQUIRE SIGNIFICANT CAPITAL INVESTMENT AND ROBUST DOMESTIC POLICY SUPPORT

The development of a robust offshore wind domestic supply chain is a necessary step to achieve the United States' ambitious clean energy goals. In addition to reducing the risk to development timelines and overreliance on foreign supply chains, a domestic supply chain ensures that jobs and economic benefits can be retained in the U.S. This is a key policy goal reflected in the Inflation Reduction Act's domestic content requirements for clean energy technologies. However, there are several economic and technical challenges that must be addressed, including limited port, vessel, and manufacturing infrastructure. While the challenges are substantial, knowledge of supply chain capacity requirements for ambitious targets will help right-size the industry towards increased economies of scale and accelerated infrastructure development.

Researchers have identified a clear and tangible path to developing supply chains that adequately support the Biden Administration's target of 30 GW of offshore wind by 2030. The approximately $22.4 billion in capital already committed is sufficient to secure manufacturing supply chains commensurate with this target, though some additional investment is likely needed in port infrastructure and vessels (Matos, Wooley, 2023). However, this supply chain investment needs to double by 2035 and double again by 2040 to approach the offshore wind ambition envisioned in the Medium and High Ambition scenarios. Our analysis suggests that in order to support an offshore wind industry that provides 20% of the nation's electricity demands, cumulative investment in the supply chain would need to exceed at least $260 billion through 2045.[8]

A detailed supply chain analysis, based upon NREL's projections of the supply chain development needs for the 30 GW by 2030 target, can be found in an accompanying report, Offshore Wind Supply Chain Development and Investment Analysis (Matos, Wooley, 2023). In that report, we estimate the required production, facilities, and investment needed to reach 100 GW by 2035 and approach the 2050 Offshore Wind Policy scenario targets described in this report. Assuming current technology, developing 500 GW of offshore wind capacity will require upwards of 30,000 finished turbines, 100,000 turbine blades, and over 115,000 miles of array and export cables, as well as over 100 new manufacturing facilities (Table 4). Manufacturing that amount of equipment domestically would require a four to fivefold increase in the estimated number of facilities or production lines needed to meet the 30 GW target by 2030.

8 For comparison, global upstream investment in upstream oil and gas is over $400 billion per year. See: Oil and gas: The investment gap dilemma and Oil, gas investments to hit $628 billion in 2022 led by upstream gas and LNG.

TABLE 4.

Facilities required for domestic offshore wind manufacturing capacity.

TARGET CAPACITY (GW)	BLADE FACTORIES	NACELLE FACTORIES	FOUNDATION FACTORIES (FIXED AND FLOATING)	TOWER FACTORIES	EXPORT CABLE FACTORIES	ARRAY CABLES FACTORIES
30[9]	5	4	5	4	4	2
100 by 2035	12	9	12	6	9	5
Low Ambition	9	7	9	7	7	4
Medium Ambition	20	16	20	16	16	8
High Ambition	30	24	30	24	24	12
Current Announced Facilities (Jan 2023)[10]	1	2	2	1	2	1
Years to construct a single facility	3-5	3-5	2-4	3-5	5-6	5-6

9 See: Shields et al., 2023.
10 See: Shields et al., 2023.

As larger capacity turbines are adopted, manufacturing is enhanced, and deployment is streamlined, these estimates may shrink.[11] For example, if the U.S. offshore wind industry were to shift toward 20 MW offshore wind turbines, approximately 25,000 turbines will be needed to reach 500 GW of total capacity, compared to over 34,000 15 MW turbines. Additionally, a shift toward greater reliance on floating turbines would shift supply chain, port, and vessel needs, particularly on the East Coast where fixed-bottom turbines are the norm. For reference, the U.S. has installed approximately 70,000 turbines on land to date, amounting to 140 GW of land-based wind capacity (USGS, 2022b).

TABLE 5.

Major offshore wind supply chain announcements in the U.S. (recreated from Shields et al., 2022).

COMPONENT	LOCATION	INVESTORS	INVESTMENT ($ MILLION)	STATUS
Blades	Portsmouth Marine Terminal (Virginia)	Siemens Gamesa	200	Announced
Nacelles (final assembly only)	New Jersey Wind Port (New Jersey)	Vestas, Atlantic Shores	Not announced	Announced
	New Jersey Wind Port (New Jersey)	GE, Ørsted	Not announced	Announced
Towers	Port of Albany (New York)	Marmen Welcon, Equinor	350	Announced
Monopiles	Paulsboro Marine Terminal (New Jersey)	EEW, Ørsted	250	Under Construction
	Sparrows Point (Maryland)	US Wind	150	Announced
Foundation platforms	Port of Providence (Rhode Island)	Eversource, Ørsted	40	Announced

Constraints on the supply chain for finished components are mostly attributed to subcomponents and raw materials. Offshore wind-related steel supply will need to double by 2030, and then double again to support 100 GW (Musial et al., 2022). While substantial, steel demand to meet the 30 GW target constitutes just one percent of annual U.S. steel production.[12] A single steel

11 Numerous wind turbine manufacturers have already announced commercially-available 18 MW turbines (See: Lewis, 2023). Moving from 13 MW to 18 MW turbines would reduce the need for around 18 units in a 1 GW wind farm, according to Chinese manufacturer Mingyang (See: Lee, 2023).

12 U.S. raw steel production was 87 million metric tons in 2021 (See: USGSa, 2022). The estimated steel required to meet 30 GW by 2030 is 886,000 tons (Shields et al., 2023).

mill being constructed by Nucor in Kentucky would meet approximately half the demand of a 100 GW national target, but may have difficulty supplying steel products to distant regions where no such capacity currently exists (Lantz et al., 2022). Similarly, Sparrows Point Steel in Maryland is expected to be constructed in about two years and produce enough monopiles to support 2.4 GW of turbines annually (Richards, 2021). Achieving 100 GW by 2035 would require at least four additional specialty steel plants in the next few years, with at least one each in the West Coast and Gulf Coast regions.

Lack of port capacity and wind turbine installation vessels (WTIV) is likely the biggest bottleneck facing the production and installation of turbines at scale. It is essential to rapidly expand existing port infrastructure to support increased offshore wind capacity, and develop new ports in select locations. Based on international best practices, it is likely that advancements in installation technology and larger capacity turbines will decrease port area requirements. For example, a major offshore wind port in Denmark plans to expand port capacity from 1.5 GW today to 4.5 GW by 2025, through the use of computer modeling to reduce port space needed for turbine assembly (Port Esbjerg, 2023).

Elsewhere, new port infrastructure is being developed to accommodate larger turbines and increased throughput. Two new port developments in the U.K. will serve 9 GW of capacity annually, at least two or three times more capacity than some existing U.S. ports are estimated to support (Ellichipuram, 2021). In Southern California, the Port of Long Beach has released plans for a 400 acre marshaling port to serve the Morro Bay lease area. Combined with the Humboldt Bay port, California's ports could support an annual installation of 1-1.5 GW per year.[13] If existing U.S. port infrastructure could scale at similar rates to those in Europe, increasing annual capacity installation, the need for greenfield port development may decrease.

Similarly, the U.S. government and private investors must commit resources within the next three to five years in order to secure the capacity of four to eight large-ship production lines able to produce enough ships to increase installed capacity beyond the 30 GW by 2030 goal. To-date, just one domestic wind turbine installation vessel (WTIV) is under construction, with plans to be operational by 2024. There were just 16 WTIVs in operation in the entire world in 2020, only six of which are capable of installing 15 MW turbines, suggesting that ship building capacity needs to increase significantly to meet both U.S. and global demand (Shields et al., 2023). Recognizing this need, shipbuilders across the globe are expanding operations, with some delivering newbuilds

13 Estimation based on Table 5 of the *California Floating Offshore Wind Regional Ports Assessment*.

in just a few years. Shipbuilder Eneti, for example, has received contracts for delivery of two new installation vessels capable of installing 20 MW turbines that will be delivered in just two years time (Anderson, 2023).

Effective industrial policy can send strong market signals to manufacturers and investors, helping to catalyze the level of investment required to meet these ambitious targets. After enactment of both the CHIPS and Science Act and the IRA in August, 2022, private industry investment is poised to flood the U.S. with new domestic manufacturing capacity for battery manufacturing facilities, solar module factories, electric vehicle plants, and other critical technology components. Over just the past 12 months, manufacturers have committed at least $227 billion in new domestic manufacturing to support new advanced technology manufacturing in these industries.[14] At the state level, New York requires Supply Chain Investment Plans and included up to $300 million in state funding as part of its most recent competitive offshore wind solicitation. Proposals from developers include commitments in several facilities and port upgrades across the state.[15]

Supply chain, port and vessel constraints pose significant challenges for the industry. Establishing critical policy support and capital investment will help achieve 2035 offshore wind deployment targets, as well as help the industry scale to meet ambitious 2050 goals. The year 2035 is a critical inflection point for the industry, in which the nation will have to demonstrate concerted and sustained investment in manufacturing facilities, port infrastructure, and workforce development.

HIGH-QUALITY WIND RESOURCES OFF THE SHORES OF ALL COASTAL STATES INCREASES OPPORTUNITIES FOR DEPLOYMENT WHILE DISPERSING ECONOMIC BENEFITS ACROSS THE NATION

The U.S. is fortunate in its high-quality wind potential across all major coastal areas. Although U.S. offshore wind activity currently is concentrated along the Northeast coast, our analysis suggests that offshore wind deployment need not be restricted to one region. Rather, offshore wind can be cost-effectively deployed along most of the U.S. coastline.

There are currently two commercial wind plants operating in U.S. waters off the coast of Virginia and Rhode Island, and the industry is rapidly expanding. Construction has started on two additional projects in New York and Massachusetts, with consideration, planning, permitting, and/or site control underway for new development off the coasts of California, Connecticut,

14 See: Inflation Reduction Act (IRA) and CHIPS and Science Act Investments.
15 See: NYSERDA 2022 Offshore Wind Solicitation; Submitted Proposals.

Delaware, Louisiana, Maine, Maryland, Michigan, New Jersey, North Carolina, Ohio, Oregon, Rhode Island, Texas, Virginia, and in the Gulf of Mexico.

The Bureau of Ocean Energy Management (BOEM) has identified additional areas for possible new wind leases off the coasts of New York, South Carolina, California, the Central Atlantic states, Oregon, and Maine, as well as in the Gulf of Mexico (off the Louisiana and Texas coasts) (Musial et al., 2022; BOEM, 2021; BOEM, 2023). Since 2014, BOEM has held lease sales in waters off the coast of Rhode Island, Delaware, Massachusetts, Maryland, New Jersey, New York, North Carolina, Virginia, and California.

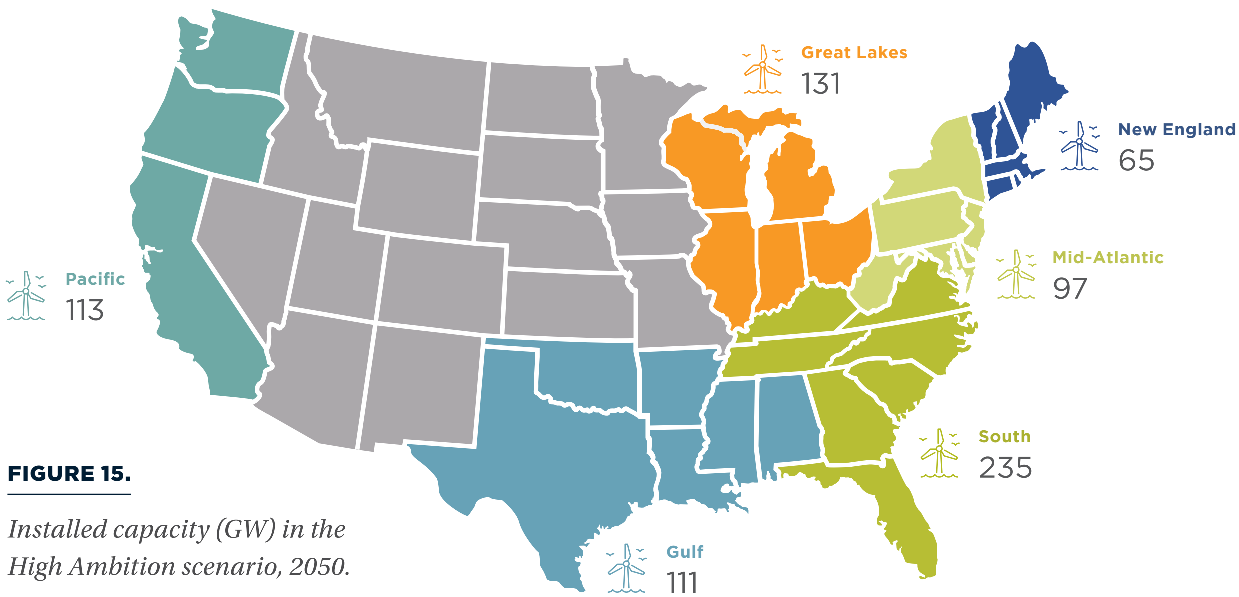


FIGURE 15.

Installed capacity (GW) in the High Ambition scenario, 2050.

Figure 15 details the installed offshore wind capacity in a High Ambition future, representing the most widespread and robust deployment of offshore wind considered in this analysis.[16] The High Ambition scenario shows potential to deploy approximately 65 GW of offshore wind in the waters off of New England, 97 GW along the Mid-Atlantic coast, 235 GW in waters off the Southeast (including Florida), 111 GW in Gulf waters, 131 GW in Great Lakes waters, and 113 GW along the Pacific coast.[17]

16 This analysis only considers the contiguous 48 states, understanding that Alaska and Hawaii have unique energy system needs that are not fully captured in our modeling.

17 ReEDS chooses to deploy fixed or floating offshore wind turbines based on the resource quality, capital cost, interconnection cost, and ocean depth. Based on our existing technology understanding, most of the offshore wind deployment on the West Coast will be floating while that on the East Coast and the Gulf will be fixed bottom. However, uncertainty remains about how technology improvements and cost declines will impact future deployment trends. While ReEDS deploys renewable resources at the state level, offshore wind is unique in that it is often sited in federal waters. We thus aggregate state-level ReEDS results to the regions described above, understanding that most offshore wind projects will be sited in federal waters and may span multiple state lines and constitute multi-state agreements. More detail is provided in the Appendix.

While offshore wind activity is currently underway along the East Coast, West Coast, and Gulf of Mexico, activity in the Great Lakes is particularly nascent. This analysis evaluates the potential for offshore wind to expand across all technically viable regions in the United States, including the Great Lakes. The Great Lakes region has high wind speeds with capacity factors often averaging over 50%. Because of its strong wind resource potential and proximity to large population centers and transmission interconnection points, the model chooses to deploy a significant amount of new offshore wind capacity in the Great Lakes region. While the model does account for technical limitations to deployment in this region, such as water depths, ecologically sensitive areas, shipping lanes, and existing infrastructure, it does not account for major political and regulatory hurdles. Offshore wind in the Great Lakes will likely have to contend with unique challenges, such as blade icing (NYSERDA, 2022). This analysis suggests that state and federal actors should further evaluate the feasibility of large-scale offshore wind development in the region, while recognizing that there remains significant technical potential across other regions of the U.S.

The ultimate challenge in deploying this magnitude of offshore wind capacity is identifying available areas and leasing viable wind energy areas at scale. Figure 16 details the scale of this deployment in the context of available offshore area. We estimate that roughly 30% of the contiguous U.S. Exclusive Economic Zone (EEZ) is technically feasible for development (Technical Potential Zone).[18] If the U.S. was able to deploy 750 GW of offshore wind by 2050 identified in the High Ambition scenario, the turbine impact area would amount to just 0.8% of offshore area suitable for development within the U.S. EEZ (Figure 16).[19] This estimate represents a high level assessment of the offshore area available to deploy new offshore wind resources. Importantly, as highlighted in the accompanying Policy Report, federal and state agencies will need to take a proactive approach to mapping conflicts and developing leasing strategies at scale with stakeholder input in order to further avoid sensitive environmental areas, critical fishery habitat, cultural resources, and other important water spaces that have not been fully evaluated in this analysis (Energy Innovation, 2023).

18 This analysis relies on siting assumptions developed by NREL (Lopez et al., 2022). Based on these assumptions, the model can only deploy offshore wind in areas shallower than 1,300 meters in depth and within the 370 kilometers of the EEZ. 60 meter ocean depth is the delineator between fixed and floating offshore wind technology. Siting assumptions also include standard exclusions and setbacks as detailed in Lopez et al., 2022. In this analysis, the EEZ is confined to the contiguous U.S., including the East Coast, West Coast, Gulf of Mexico, and Great Lakes regions.

19 For purposes of this analysis, turbine impact area is defined as the area directly consisting of turbines and foundations (as well as associated wake and scour effects). We assume a 200m radius from the turbine foundation is affected by wake and scour effects and becomes unusable for any other purpose (BOEM, 2020). The 200m radius is an upper bound estimate of the area affected.

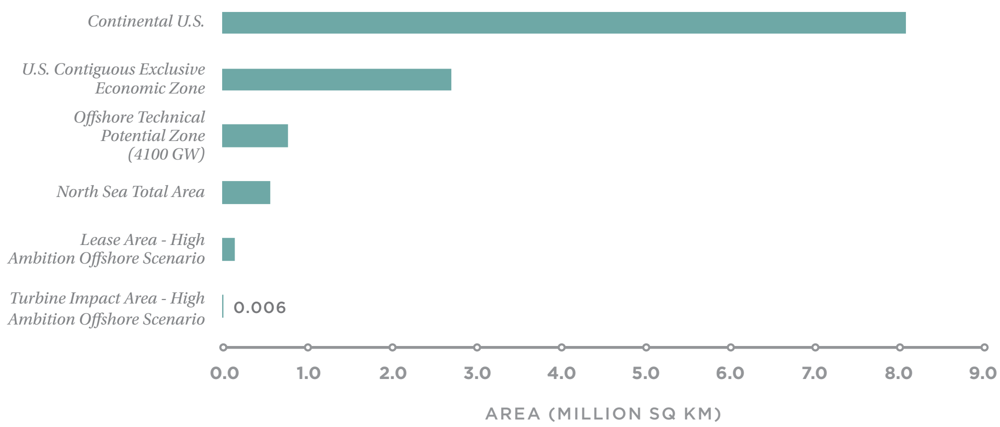
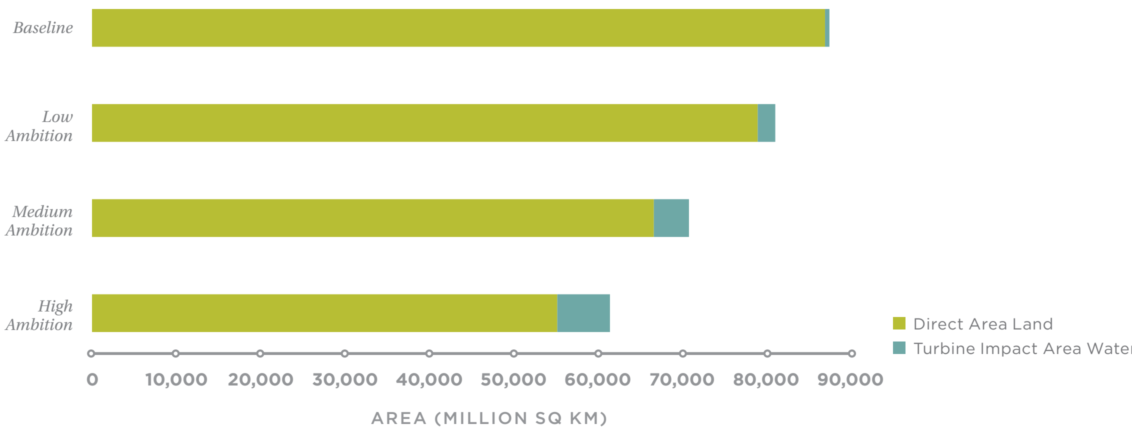


FIGURE 16.

The turbine impact area (including turbines, foundations, and associated wake and scour effects) of offshore wind in the High Ambition scenario, relative to the total lease area, the total available area in the North Sea, the U.S. Technical Potential Zone (4100 GW), the contiguous U.S. Exclusive Economic Zone, and the Continental U.S., 2050.

Achieving 100% clean electricity will require a vast build-out of new renewable energy resources, both on land and offshore. To date, the U.S. has deployed over 220 GW of wind and solar, with a leased area of approximately 7.1 million acres of land (Merrill, 2021). In our Baseline scenario, the U.S. deploys over 3,400 GW of new renewables to meet near-net zero emissions in 2050. While the proposed land-based renewable deployments would span nearly 72 million total acres of land, the area directly sited with solar plants and wind turbines is far smaller — just 21 million acres. For wind energy, the projects typically have multiple uses in addition to energy production. An estimated 40% of land-based wind plants in the U.S. are located on cropland, while 55% are located on rangeland (USDA, 2017).

The U.S. has vast, untapped potential to generate clean power off its coasts. Our analysis demonstrates that as offshore wind deployment increases, the area directly utilized by wind turbines and solar panels (the Direct Impact Area) decreases overall (Figure 17), largely because less renewable energy is deployed on land. In the High Ambition scenario, the U.S. is able to reduce the direct land and water impacts by nearly 25,000 square kilometers relative to Baseline (6 million acres). While the total area of leased water increases as ambition increases, only a small fraction of this area will be directly occupied by turbines and foundations.[20] Other nations with similar net zero targets plan to deploy far more generation resources in smaller areas. The North Sea, for example, plans to host 300 GW of offshore wind in 2050 — in an area just one-fifth the size of the entire U.S. EEZ (Figure 16).



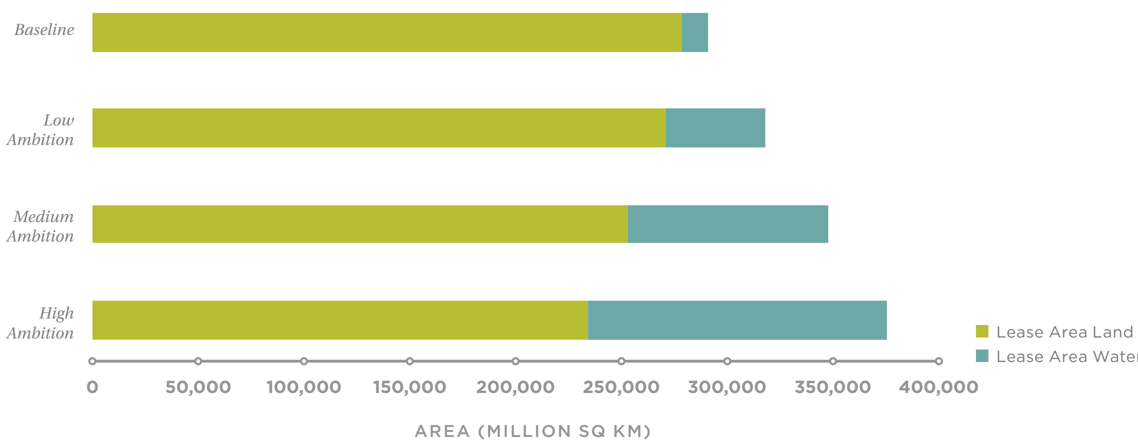


FIGURE 17.

Direct area (sq. km) impacted (including solar plants, wind turbines, foundations, and associated wake and scour effects) (top), and total leased area (sq. km) (bottom), in the Baseline, Low, Medium, and High Ambition scenarios, 2050.

20 The area consisting of offshore wind plants, like onshore wind plant areas, might serve multi-use purposes. For this reason, we highlight the amount of space devoted specifically to turbines and foundations (as well as associated wake and scour effects). However, other use limitations to wind plant sites may apply, such as during the construction process and for ongoing maintenance and operations.

COORDINATED TRANSMISSION PLANNING CAN REDUCE INTERCONNECTION COSTS BY 35% AND ACCELERATE DEPLOYMENT TIMELINES

A net zero electricity grid will require significant new investment in transmission infrastructure in order to distribute clean energy generation across a larger footprint. Many national decarbonization studies have demonstrated the value of additional, high-voltage transmission. Princeton's Net-Zero America, for example, envisions high-voltage transmission capacity tripling by 2050 to support a high electrification, net zero future (Larson et al., 2021). However, transmission infrastructure is historically difficult to permit and construct. Offshore wind provides an opportunity to rethink the transmission planning and interconnection process and avoid the backlog that existing interconnection processes have produced on land. Backlogged engineering studies and delays in permitting have stalled over 2,000 GW of wind, solar, and storage in interconnection queues across the country (Rand et al., 2023). These delays not only slow the deployment of clean energy and the nation's shift to a net zero economy, they have resulted in rising interconnection costs. MISO and PJM recorded average interconnection costs of \$120/kW in 2021, 65% higher than those seen in 2015-2019 (BNEF, 2023a).

In order to meet the 95% clean electricity target and increased electricity demand in the Offshore Wind Policy scenarios, we estimate that bulk transmission system capacity must double by 2050 relative to 2023 levels. The Baseline scenario analysis identifies a need for $402 billion in new transmission system investments between 2023 and 2050 (Figure 18), with the investment allocated fairly evenly between lines that connect new power plants to the high voltage network ("spurlines") at 55%, or $220 billion, and bulk transmission system upgrades at 45%, or $182 billion.[21]

The High Ambition scenario involves a total transmission investment of $719 billion, approximately 80% greater than that in the Baseline scenario, primarily due to the more extensive spurline development required to connect offshore wind generation facilities to the land-based grid. Spurlines account for the majority of transmission investments (74%, or $532 billion), while investments in bulk transmission remain relatively in line with those of the Baseline scenario (24%, or $187 billion). However, this increase in spurline cost does not reflect best practices to managing interconnection costs through holistic planning — concepts explored in the sensitivity analysis, as well as our companion Transmission Analysis and Policy Report (Daymark Energy Advisors, 2023; Energy Innovation, 2023).

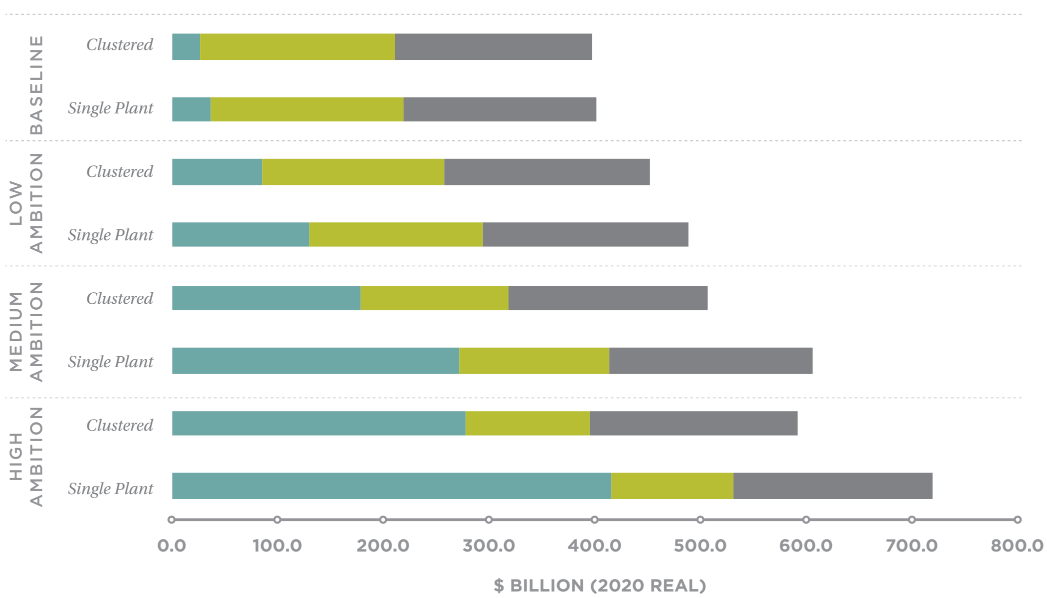


FIGURE 18.

Investment ($ billion) in spurlines (on land and in water) and bulk transmission lines in the Baseline, Low, Medium, and High Ambition scenarios, clustered and single plant approach, 2050.

21 Spurline transmission refers to lines needed to connect remote renewable energy generation to the bulk transmission system or load centers. Bulk transmission refers to larger, higher-capacity transmission lines designed to carry electricity across long distances at high voltages, typically above 115 kV.

In our analysis, offshore wind interconnection costs are estimated on a single plant basis, meaning that a single offshore wind plant (600 MW) is individually connected to the closest available onshore grid connection. This conceptual approach is similar to that detailed by NREL and Bloomberg New Energy Finance (BNEF) and results in expected interconnection costs ranging from $800-$1100/kW (Beiter et al., 2016; BNEF, 2021). These interconnection costs, which can ultimately comprise 20-30% of total offshore wind plant investment cost, are higher for offshore wind than land-based wind. This approach also typically requires upgrades to the onshore transmission network to facilitate the interconnection.

Clustering multiple offshore wind plants together and connecting them to the onshore grid using a single high-voltage line can significantly reduce interconnection (spurline) costs, while increasing resource optimization, economies of scale, and energy output (Figure 19). It also has knock-on effects, explored in the policy report and a Brattle analysis, of improving developer certainty, facilitating greater competition, reducing environmental and community impacts, and potentially improving grid resilience (Pfeifenberger et al., 2023; Energy Innovation, 2023). This sharing of high-voltage transmission infrastructure, including converter stations and submarine cables, could reduce U.S. offshore wind spurline costs by 35% on average, as explained in detail in the Appendix. If all plants in the High Ambition scenario are connected to the onshore transmission system using the clustered interconnection approach, the offshore spurline costs are reduced by approximately $135 billion (from $532 billion to $397 billion) (Figure 18). The national grid operator in the United Kingdom, National Grid, estimated that the clustered approach can lower the capital and operating expenditure of the transmission system by 18% between 2018 and 2050 (National Grid ESO, 2022). This approach is similar to the land-based transmission plan conducted by the grid operator in Texas (ERCOT) known as Competitive Renewable Energy Zones (CREZ) (Cohn, 2020).

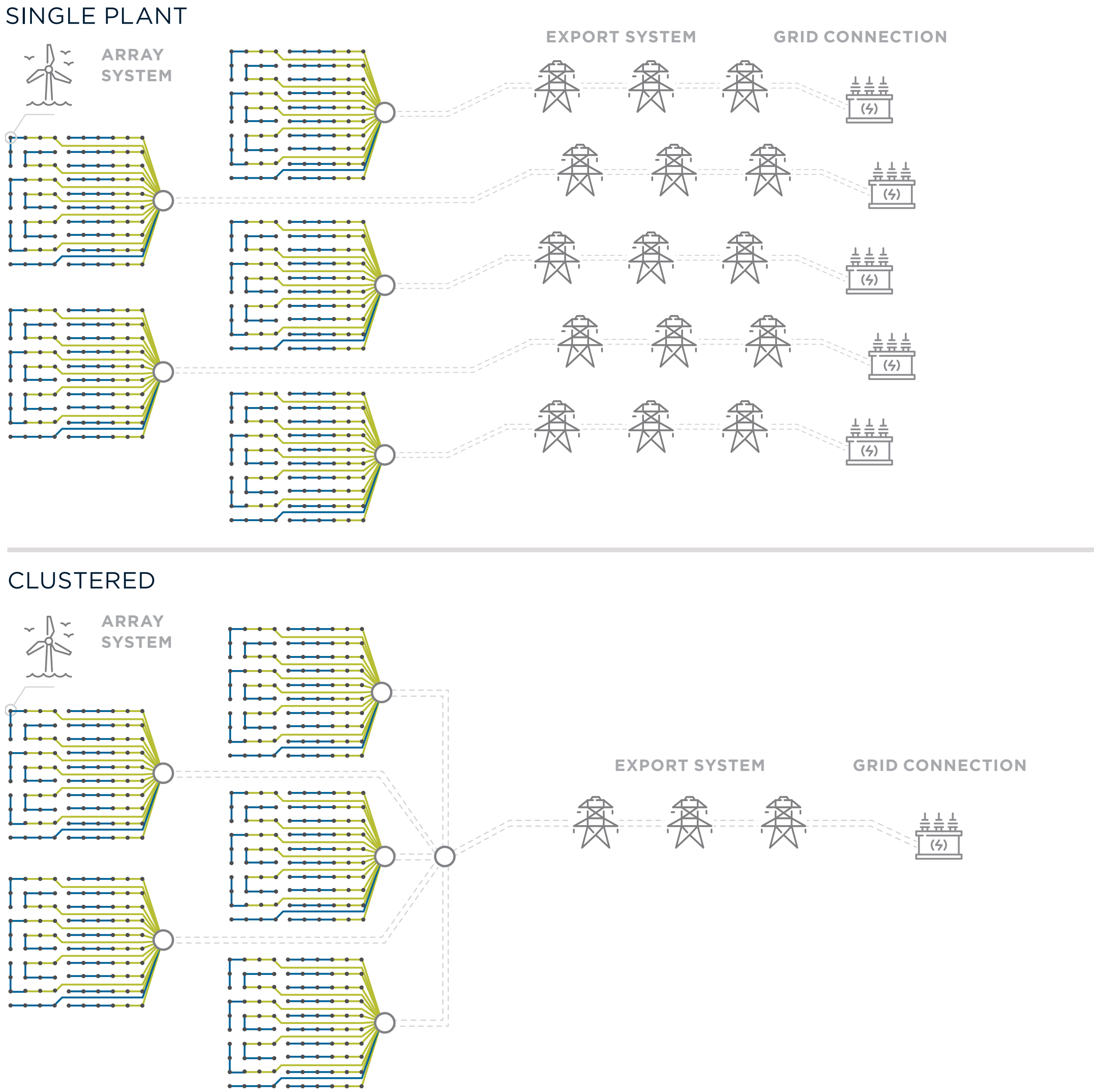


FIGURE 19.

Representative display of a single plant interconnection approach and a clustered transmission interconnection approach. Source: Based on Figure 24 (Beiter et al., 2016).

The top figure represents the single plant interconnection approach, in which each offshore wind plant has its own set of collection, transport, and delivery infrastructure. In this approach, each wind turbine's energy generation is aggregated through a feeder circuit, which is then delivered via its own transmission cable to a grid connection point on land. Under this approach, export costs increase linearly with both wind plant capacity and distance to shore, making it difficult to gain economies of scale or reduce interconnection costs. The bottom diagram illustrates a clustered transmission interconnection approach. In this case, multiple offshore wind plants are aggregated together through feeders and the aggregated wind power is then transported to a grid connection via a single, high-voltage export system and delivered to a single grid connection. Multiple wind plants are thus able to share the high-voltage transmission infrastructure, including converter stations and submarine cables. The result is a significant reduction in overall interconnection costs, which helps reduce the capital cost of each installed wind project.

The clustered transmission approach allows for greater aggregation of offshore wind production into fewer collection points, ultimately reducing costs. Clustering allows multiple offshore wind plants to share transmission infrastructure, which promises two major efficiency gains. Clustering enables developers to build fewer, higher capacity, higher voltage submarine cables to reduce the amount of total assets, and higher voltage transmission of wind generation allows for lower losses in energy. The clustered approach can also make it economically feasible to access high quality wind resources at locations further from shore, while limiting seabed disturbances and reducing the number of onshore crossings (Pfeifenberger et al., 2023).

Bulk transmission capacity increases to comparable levels in the Baseline (to approximately 276,000 GW-miles) and High Ambition (to 268,000 GW-miles) scenarios by 2050. However, a heavier reliance on offshore wind also shifts new bulk transmission infrastructure investments to different locations: from the middle of the country for the Baseline scenario toward the coast for the Offshore Wind Policy scenarios (Figure 20). Bulk transmission costs are higher per GW-mile along the coast than those found inland, resulting in slightly higher bulk transmission costs for the Offshore Wind Policy scenarios.

FIGURE 20.

New bulk transmission lines in the High Ambition scenario, 2050.

NEW TRANSMISSION CAPACITY (MW)

1
100
10,000

OFFSHORE WIND GENERATION CAN EFFECTIVELY BALANCE LAND-BASED RENEWABLE GENERATION TO SUPPORT A DEPENDABLE GRID

A diverse portfolio of clean energy technologies, buoyed by a new influx of offshore wind, is critical to ensuring future grid dependability with the anticipated major increases in energy demand through 2050. Not only can offshore wind provide abundant energy, its generation patterns are particularly complementary to existing clean energy technologies.

It is anticipated that economy-wide electrification will shift national peak load periods from summer afternoons to winter mornings. Our analysis suggests that achieving near-net zero emissions by 2050 through electrification of the economy will result in the annual demand for electricity to soar to 10,700 TWh, with daily peak demand reaching over 2,100 GW in the winter. In this section, we examine the generation impacts of the High Ambition scenario, in order to demonstrate the dependability of a grid operating with extremely high levels of offshore wind and other renewable energy generation.

Dennis Schroeder / NREL

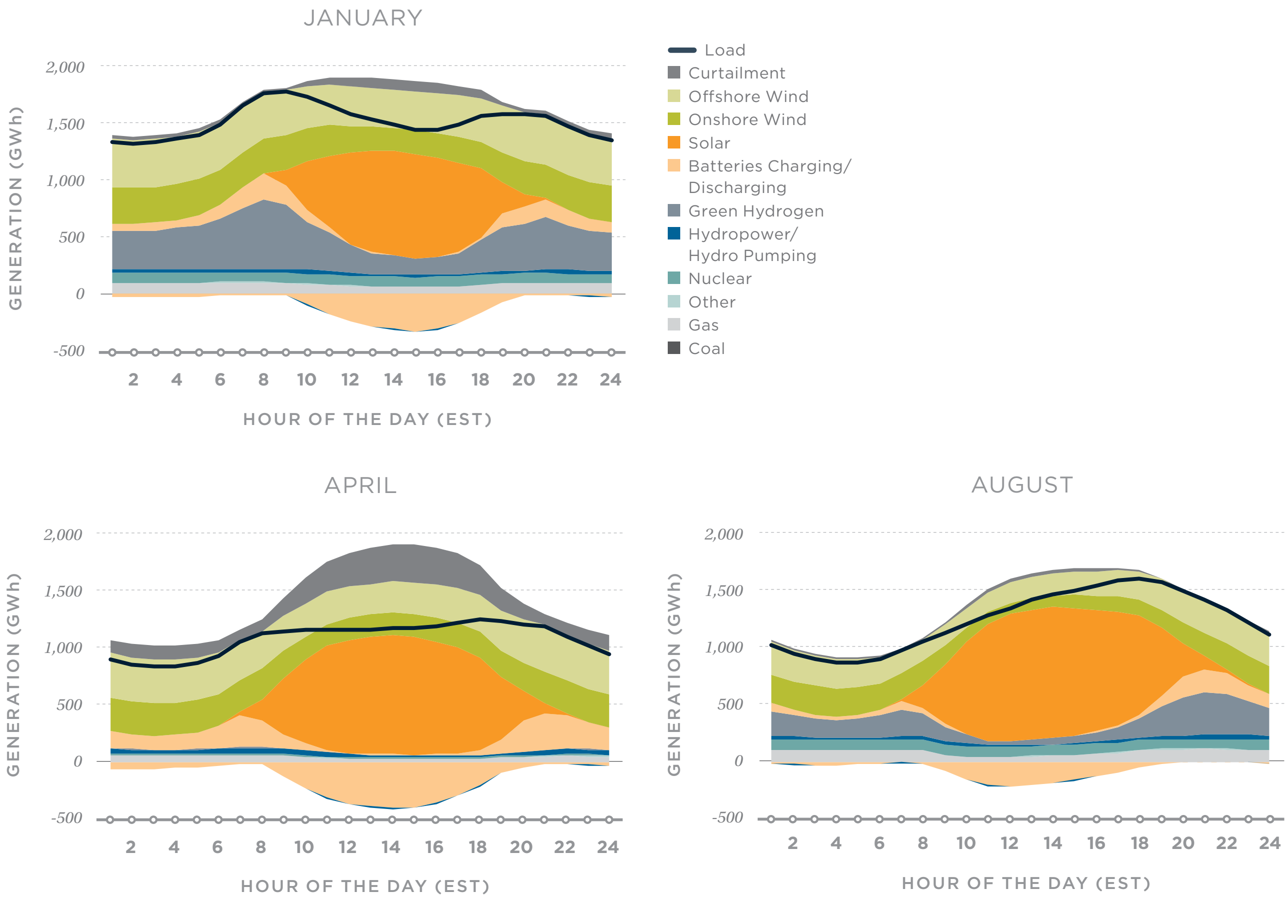


FIGURE 21.

National average hourly generation dispatch in the High Ambition scenario, January, April, and August, 2050.

During periods of normal demand and generation, a combination of solar, offshore and land-based wind, and new battery storage are largely sufficient to meet load. Batteries are particularly critical to meet the demand during non-solar evening hours. During periods of high demand, other resources such as green hydrogen combustion turbines ramp up to fill rising energy demand.

During normal periods of generation and demand, the portfolio of land-based wind, solar, and offshore wind, combined with battery storage, is sufficient to meet energy needs, providing 80%-90% of total electricity generation (Figure 21, Figure 22). During periods of high demand, particularly in peak winter months such as January, other resources ramp up to fill rising energy demand. In particular, green hydrogen combustion turbines (CT) help compensate for mismatches in demand and renewable generation. This is not a prediction of hydrogen's role in the power sector, but rather reflects the fact that resources low in capital cost and high in variable cost are complementary with high shares of variable renewables. Green hydrogen CTs contribute approximately 6-7% of total generation in 2050 in all Offshore Wind Policy scenarios, providing a reliable backup during periods of low renewable production or high demand. In the Baseline scenario, green hydrogen CT generation accounts for 9% of total generation, slightly higher than in the Offshore Wind Policy scenarios. The Baseline scenario requires slightly greater reliance on hydrogen generation as a result of less offshore wind generation, which typically has a high capacity factor and can thus provide additional generation. It is important to note that power systems with high proportions of renewables will likely require firm generation, but the exact resource mix and technology may change depending on future cost declines and technology improvements.[22]

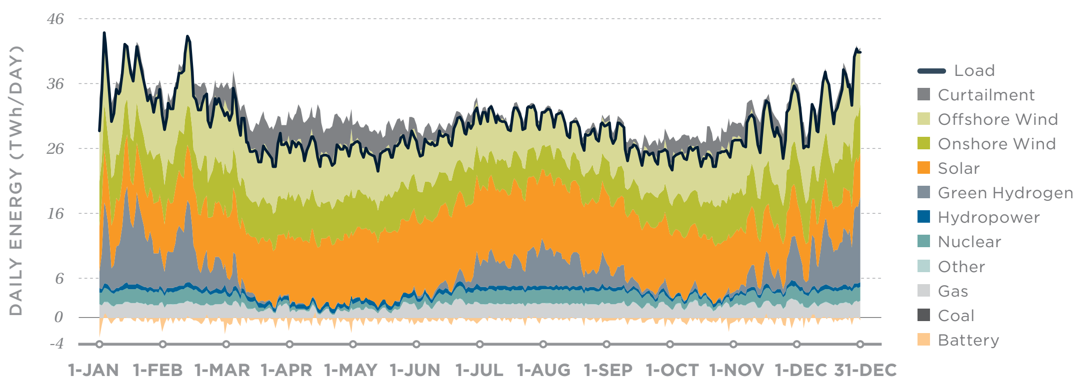


FIGURE 22.

National daily energy balance in 2050 in the High Ambition scenario, averaged over seven weather years.

During periods of normal demand and generation, such as April, the dispatch stack is dominated by offshore wind, solar, land-based wind, and battery discharge. In months with higher demand or lower renewable generation, green hydrogen CT generation increases to meet demand.

To highlight the dependability of a 95% clean electricity grid in 2050, showcase how generation patterns of renewable resources balance each other, and estimate firm capacity requirements, we identified the period during the seven weather years that experienced the largest gap between clean electricity generation (including battery generation) and load.

22 NREL's recent report, *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035* offers additional insight into the complexity of modeling 100% systems (Denholm et al., 2022). In this analysis, NREL relies on numerous new technologies to "mitigate supply/demand imbalances over longer timescales." For example, a core scenario that does not rely on carbon capture and sequestration requires close to 700 GW of hydrogen CTs. For comparison, our Offshore Wind Policy scenarios install approximately half that amount in 2035.

The maximum net load period, when hydrogen CT generation reaches its peak of 1,080 GW, occurs on January 19th in one of the weather years (2011) (Figure 23). At 7:00 am Eastern Time on that day, solar generation is near zero, while onshore wind generation is as high as 228 GW, or 40% of its installed capacity. The total system demand of about 2,011 GW is met by a combination of offshore wind generation (316 GW, representing about 45% of installed capacity) and other clean resources, such as hydropower and nuclear (140 GW total), approximately 1,080 GW of hydrogen CT's, and 155 GW of battery storage discharge.

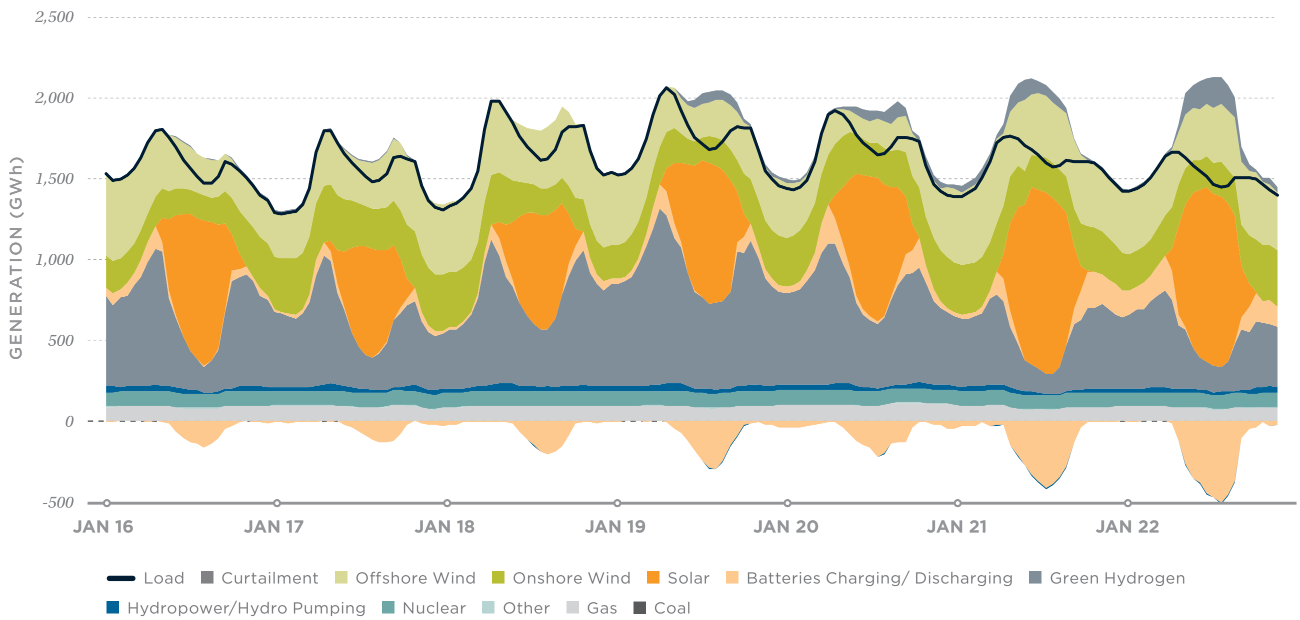


FIGURE 23.

National dispatch, High Ambition scenario, during the maximum net load week over seven weather years (2050).

Across seven weather years, the hydrogen capacity requirements proved to be highest in the winter months (December-February), when solar generation falls significantly and demand picks up due to increased electrification demand. Hydrogen CT generation above 500 GW is required for fewer than 100 hours per year across the seven-year simulation. Of the 1,080 GW of hydrogen CT dispatched in 2050 in the High Ambition scenario, 500 GW have a capacity factor less than 1%, meaning that resources are used very infrequently (Figure 24). Further research is needed to understand the interactions between industrial end-uses, the hydrogen economy, and demand to explore the role of hydrogen in a zero-carbon economy with higher fidelity.

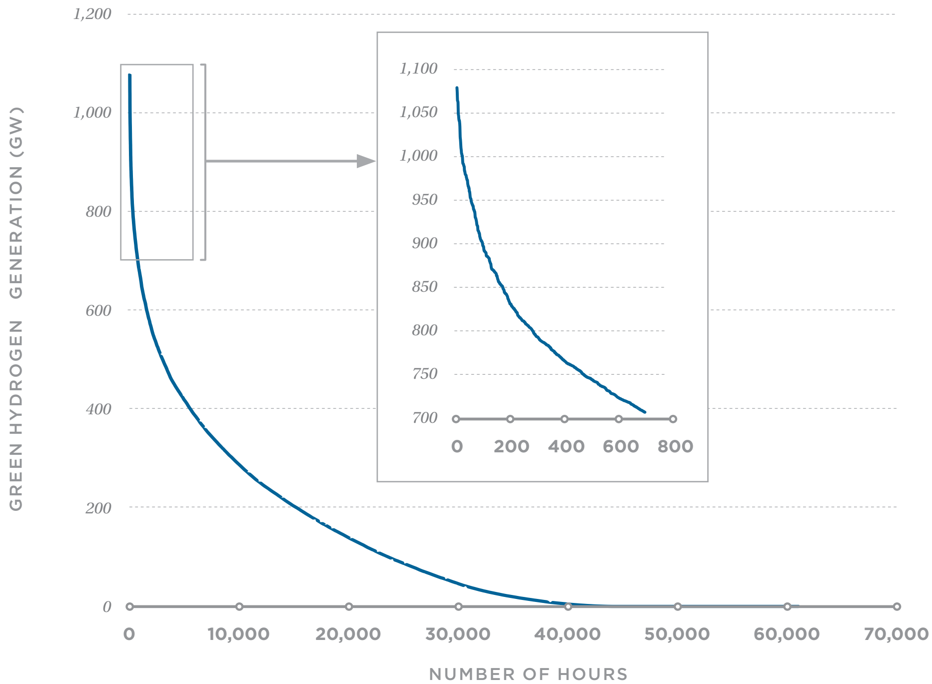


FIGURE 24.

Duration curve of green hydrogen CT generation over seven weather years.[23]

Nearly 40% of total installed green hydrogen CT capacity, approximately 500 GW, has a capacity factor of less than 1%, meaning that these peaking resources run infrequently.

This modeling approach represents a conservative strategy for achieving 95% clean electricity. Other technology alternatives not considered in this analysis, such as demand response, energy efficiency, or flexible load, may be more cost-effective for system balancing in peak hours. Various complementary approaches could help achieve this deep decarbonization pathway, with potential for even lower system costs and accelerated emissions reductions. For example, flexible loads such as responsive electric vehicle charging, water heating, or large industrial loads, including electrolysis, could respond to changing grid conditions faster and more cost-effectively than conventional power generators. Flexible loads could similarly take advantage of zero or negatively priced electricity that is likely to occur during hours of curtailment, with the potential to increase the overall clean energy share. Other technologies like advanced geothermal, advanced nuclear, long-duration storage, carbon capture, and hydrogen fuel cells could further diversify the technology set

23 Note that 2007-2013 did not have particularly severe winter storms compared to some other periods. Therefore, for a more robust analysis, additional assessment including simulations over 30 weather-years may be needed.

explored in our net zero scenarios, which were designed to principally focus on the impacts of offshore wind deployment.

SCALING THE DOMESTIC OFFSHORE WIND INDUSTRY COULD CREATE NEARLY 390,000 JOBS AND SPUR ECONOMIC ACTIVITY ACROSS THE COUNTRY

Scaling a domestic offshore wind industry has the potential to bring new jobs, revitalize local communities, spur domestic manufacturing, and further stimulate the entire U.S. economy through increased economic activity. When isolating the impacts of just offshore wind development, the High Ambition offshore wind policy scenario could employ approximately 390,000 people across the economy in 2050 (Figure 25). In order to evaluate the macroeconomic and employment impacts of a targeted deployment of offshore wind, we partnered with Cambridge Econometrics using their E3ME model, a macroeconometric model designed to assess global energy and environmental policy impacts. For the purposes of this analysis, we only modeled the High Ambition offshore wind policy scenario, in order to understand the greatest potential macroeconomic impacts of the industry's growth. Additional details of this analysis are provided in the accompanying report, *Assessing the Economic Impacts and Supply Chain Development of Offshore Wind in the US* (Hodge et al., 2023).

Cambridge Econometrics examined alternative scenarios to evaluate the energy transition modeled in the *2035 Report 3.0*, with both modest and ambitious domestic content supply chain futures. Outputs from the ReEDS capacity expansion tool, including total investment by energy technology, electricity prices, and power sector capacity are used as inputs to the E3ME model to produce macroeconomic and employment results. The E3ME utilizes a different baseline than the main 2035 Report scenarios in order to better understand the changes that occur as a result of decarbonization pathways.

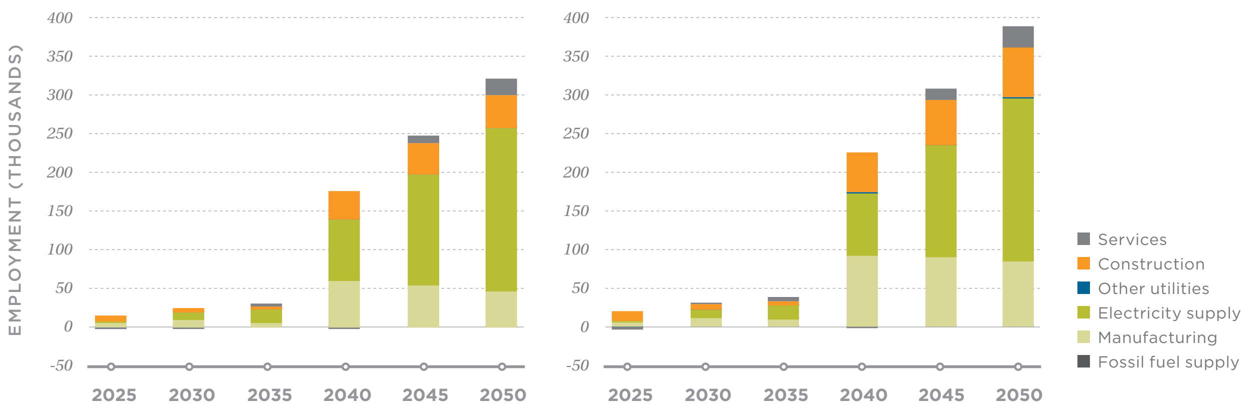


FIGURE 25.

Employment contributions of the offshore wind industry in the High Ambition offshore wind scenario under the Modest and Advanced Domestic Content Strategies, 2025-2050.

Cambridge Econometrics evaluated the impact of developing domestic supply chains versus sourcing labor and material from overseas. These scenarios alter the percentage of goods and materials sourced domestically, creating *Modest Development* and *Ambitious Development* trajectories. The robust development of domestic supply chains in the *Ambitious Development* scenario, which has the effect of creating more manufacturing jobs for offshore wind components within the U.S., and increased demand (and therefore employment) across other goods and services in their domestic supply chains, would lead to an additional 65,000 people employed relative to a Modest domestic content strategy.

Approximately half of new offshore wind jobs (210,000 in 2050) are in the electricity sector related to operations and maintenance of the system. In the near term, these jobs are concentrated in the Northeast, where a significant amount of new capacity comes online. Throughout the study period, these jobs eventually spread to the South, Gulf, Great Lakes, and West Coast regions as capacity installations spread to these areas. The other half of new jobs are related to construction, manufacturing, and other induced impacts. Manufacturing employment is heavily impacted by domestic content assumptions — of the 65,000 additional jobs created in the Ambitious Development scenario relative to the *Modest Development* scenario, 40,000 are concentrated in manufacturing. Shoring up domestic supply chains to increase U.S. manufacturing would provide a substantive boost to overall employment opportunities.

Importantly, the employment and economic benefits of domestic offshore wind development are scattered across the entire country. The majority of job impacts are concentrated where current planned offshore deployment is highest (such as the Northeast and Mid-Atlantic), while manufacturing and related jobs spread throughout the nation as offshore wind deployment increases. As offshore wind deployment spreads across the country over the years, employment trends generally track the installed capacity. In the next 10-15 years modeled, about 60% of employment opportunities are concentrated in the East Coast, New England, Mid-Atlantic, and South. Overtime, this shifts as capacity deployment trends shift (Figure 26). In 2050, for example, the South accounts for 28% of employment.

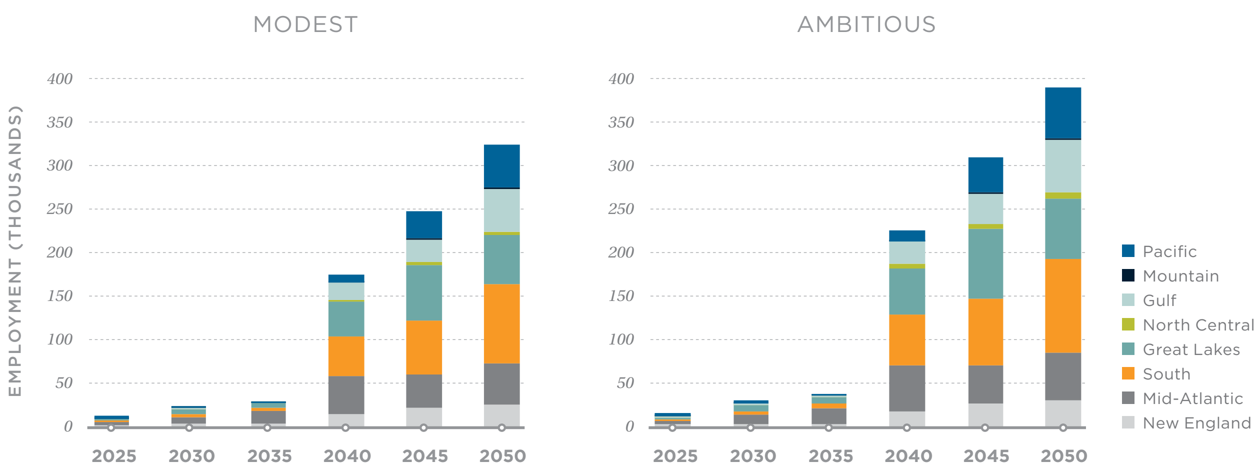


FIGURE 26.

Employment contributions of the offshore wind industry by region in the High Ambition offshore wind policy scenario under Modest and Ambitious Domestic Content Strategies, 2025-2050.

Overall impacts to national Gross Domestic Product are strongly linked to the pathway of investment over time. The High Ambition offshore wind scenario results in significantly higher investment in offshore wind technology, but more modest investments in battery storage and land-based solar and wind, as a result of the high performance of offshore wind. Depending on the domestic content of local supply chains, this scenario can boost long-term GDP modestly — approximately 0.1 to 0.2% — relative to Baseline, which equates to approximately $40 billion (in 2021 prices) in additional U.S. annual economic activity by 2050.

Supporting workforce development to enable this level of job growth is not a foregone conclusion and policy interventions will be required. The Energy Innovation policy report explores workforce development policies to complement deployment targets and ensure that workforces are ready to support rapid scaling of offshore wind while maximizing economic benefits for communities impacted by offshore wind development.

CONCLUSION

As of August 2022, there were just 42 MW of commercial-scale offshore wind operating in U.S. waters. Scaling the offshore wind industry to provide 10-25% of the nation's 2050 electricity demand will require an ambitious, long-term policy agenda, robust industrial policy support, and large investments in the supply chain, infrastructure, and transmission systems. The challenges are immense, but not insurmountable. In order to achieve net zero targets, the U.S. will need to deploy more new generating capacity than ever before — both on land and water. But the benefits can be huge — development of the U.S. offshore wind industry would provide a highly productive, reliable clean energy resource needed to help achieve a 2050 economy-wide net zero target, alongside ambitious land-based renewable energy development.

The U.S. has one of the highest offshore wind potentials in the world. The clean energy resource can be effectively integrated into the U.S. power grid without substantially impacting wholesale electricity costs. As electricity demand increases due to electrification trends, offshore wind can strengthen and de-risk the U.S. pathway towards power sector decarbonization. High-quality offshore wind is abundant across the entire U.S. coastline, increasing the opportunities for deployment while expanding and diversifying economic opportunities. As a complementary resource to land-based wind and solar, offshore wind is well-suited to meet the energy demands of a net zero energy system. Scaling the industry will require robust capital investment and durable domestic policy support to advance supply chain and infrastructure development, but doing so could support nearly 390,000 jobs in the offshore wind industry in 2050.

A companion report from Energy Innovation describes the key policy recommendations to enable an equitable, sustained commitment to offshore wind development in the United States (Energy Innovation, 2023).

ADDITIONAL 2035 REPORT RESOURCES

Technical Appendix

Policy Priorities to Ensure Offshore Wind Plays a Central Role in our Net-Zero Future

Enabling Offshore Wind Development Through Effective Transmission Planning

Assessing the Economic Impacts and Supply Chain Development of Offshore Wind in the US

Offshore Wind Supply Chain Development and Investment Analysis

2035 Report 1.0: Plummeting Solar, Wind, and Battery Costs Can Accelerate our Clean Electricity Future

2035 Report 2.0: Plummeting Costs and Dramatic Improvements in Batteries Can Accelerate our Clean Transportation Future

REFERENCES

1. Anderson, P. 2023. *Eneti Drops Plans to Build Jones Act-Compliant WTIV*. Rigzone.
2. American Clean Power (ACP). 2023. *Offshore Wind Market Report 2023*.
3. Beiter, P., Musial, W., Smith, A., Kilcher, L., Damiani, R., Maness, M., Sirnivas, S., Stehly, T., Gevorgian, V., Mooney, M., and Scott, G. 2016. *A Spatial-Economic Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030.* U.S. Department of Energy, Office of Scientific and Technical Information.
4. Blair, N., DiOrio, N., Freeman, J., Gilman, J., Janzou, S., Neises, T., and Wagner, M. 2018. *System Advisor Model (SAM) General Description (Version 2017.9.5).* NREL/TP-6A20-70414.
5. Bloomberg New Energy Finance (BNEF). 2021. *Offshore Wind-to-Hydrogen Sounds A Starting Gun.*
6. Bloomberg New Energy Finance (BNEF, 2022). 2022. Offshore Wind Market Report 2022.
7. Bloomberg New Energy Finance (BNEF, 2023). 2023. Offshore Wind Market Report 2023.
8. Bloomberg New Energy Finance (BNEF, 2023a). 2023. *A Power Grid Long Enough to Reach the Sun is Key to the Climate Fight.*
9. Bloomberg New Energy Finance (BNEF). 2023. Sustainable Energy in America 2023 Factbook.
10. Buljan, A. 2023. *China Leads in New Offshore Wind Capacity Second Year in Row, Likely to Preserve Top Position in 2023*. Offshorewind.biz.
11. Bureau of Ocean Energy Management (BOEM). 2020. *Comparison of Environmental Effects from Different Offshore Wind Turbine Foundations*. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Headquarters, Sterling, VA.
12. Bureau of Ocean Energy Management (BOEM). 2021. *Offshore Wind Leasing Path Forward 2021-2025*.
13. Bureau of Ocean Energy Management (BOEM). 2023. *Renewable Energy, State Activities.*
14. Cohn, J., and Jankovska, O. 2020. *Texas CREZ Lines: How Stakeholders Shape Major Energy Infrastructure Projects*; Baker Institute for Public Policy. Rice University, Houston, Texas.
15. The Business Council for Sustainable Energy (BCSE). *2023. Sustainable Energy in America 2023 Factbook*.
16. Daymark Energy Advisors. 2023. *Enabling Offshore Wind Development Through Effective Transmission Planning*.
17. Denholm, P., Brown, P., Cole, W., Mai, T., Sergi, B., Brown, M., Jadun, P., Ho, J., Mayernik, J., McMillan, C., and Sreenath, R. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035.*

18. Department of Energy, Wind Energy Technologies Office (WETO). 2023. *A Driving FORCE for Projecting Offshore Wind Energy Costs*.

19. Ellichipuram, U. 2021. *UK announces $132m investment in offshore wind ports - Power Technology*. Power Technology.

20. Energy Efficiency & Renewable Energy (EERE). 2023. *Floating Offshore Wind Shot*.

21. Energy Exemplar. 2023. *https://www.energyexemplar.com/plexos*.

22. Energy Information Administration (EIA). 2023. *Form EIA-860*.

23. Energy Innovation. 2023. *Policy Priorities to Ensure Offshore Wind Plays a Central Role in our Net-Zero Future*.

24. European Commission. 2023. *Member States agree new ambition for expanding offshore renewable energy*.

25. Evans, S. 2019. *Analysis: Record-low price for UK offshore wind cheaper than existing gas plants by 2023.* Carbon Brief.

26. Federal Energy Regulatory Commission (FERC). 2023. *Energy Infrastructure Update for December 2022.*

27. Gaertner, E., Rinker, J., Sethuraman, L., Zahle, F., Anderson, B., Barter, G., Abbas, N., Meng, F., Bortolotti, P., Skrzypinski, W., Scott, G., Feil, R., Bredmose, H., Dykes, K., Shields, M., Allen, C., and Viselli, A. 2020. *Definition of the IEA 15-Megawatt Offshore Reference Wind.* National Renewable Energy Laboratory.

28. Global Energy Monitor (GEM). 2023. Summary Tables - Global Energy Monitor.

29. Global Wind Atlas. 2023.

30. Global Wind Energy Council (GWEC). 2023. *Global Wind Report 2023*.

31. Henley, Jon. 2023. *European countries pledge huge expansion of North Sea wind farms*. The Guardian.

32. Hodge, D., Stenning, J., and Furbush, A. 2023. *Assessing the Economic Impacts and Supply Chain Development of Offshore Wind in the US. Cambridge Econometrics*.

33. Jenkins, J.D., Farbes, J., Jones, R., Patankar, N., and Schivley, G. 2022. *"Electricity Transmission is Key to Unlock the Full Potential of the Inflation Reduction Act," REPEAT Project,* Princeton, New Jersey.

34. Kuhn, F., Liebach, F., Matthey, T., Schlosser, M., and Zivansky, J. 2022. *How to succeed in the expanding global offshore wind market*.

35. Lantz, E., Barter,G., Gilman, P., Keyser, D., Mai, T., Marquis, M., Mowers, M., Shields, M., Spitsen, P. and Stefek, J. 2021. *Power Sector, Supply Chain, Jobs, and Emissions Implications of 30 Gigawatts of Offshore Wind Power by 2030*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-80031.

36. Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik, E., Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K. and Swan, A. 2021. *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*; Princeton University, Princeton, New Jersey.

37. Lazard. 2021. *Levelized Cost of Energy Analysis – Version 15.0.*

38. Lee, A. 2023. *China's Mingyang looks 'beyond 18MW' with 140-metre blade offshore wind turbine giant.* Recharge News.

39. Lewis, M. 2023. *A colossal 18 MW wind turbine is about to debut in China*. Electrek.

40. Lopez, A., Mai, T., Lantz, E., Harrison-Atlas, D., Williams, T., and Maclaurin, G. 2021. *Land use and turbine technology influences on wind potential in the United States.* National Renewable Energy Laboratory.

41. Lopez, A., Green, R., Williams, T., Lantz, E., Buster, G., and Roberts, B. 2022. *Offshore Wind Energy Technical Potential for the Contiguous United States.* U.S. Department of Energy Office of Scientific and Technical Information.

42. Maritime Blog. 2022. *U.S. Offshore Wind WTIV Jones Act Compliance*.

43. Matos, J. and Wooley, D. 2023. *Offshore Wind Supply Chain Development and Investment Analysis*. Goldman School of Public Policy. University of California, Berkeley.

44. Merrill, D. 2021. *The U.S. Will Need a Lot of Land for a Zero-Carbon Economy*. Bloomberg News.

45. Murphy, C., Mai, T., Sun, Y., Jadun, P., Muratori, M., Nelson, B., and Jones, R. 2021. *Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-72330.

46. Musial, W., Spitsen, P., Duffy, P., Beiter, P., Marquis, M., Hammond, R., and Shields, M. 2022. *Offshore Wind Market Report: 2022 Edition*.

47. National Aeronautics and Space Administration (NASA). 2023. Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2).

48. National Grid ESO. 2020. *Holistic Approach to Offshore Transmission Planning in Great Britain.*

49. National Grid ESO. 2022. *Offshore Coordination Project.*

50. National Grid ESO. 2023. *The Pathway to 2030 Holistic Design Network.*

51. National Renewable Energy Laboratory (NREL). 2020. *Annual Technology Baseline.*

52. National Renewable Energy Laboratory (NREL). 2021. *Annual Technology Baseline.*

53. National Renewable Energy Laboratory (NREL). 2022. *Annual Technology Baseline.*

54. National Renewable Energy Laboratory (NREL). 2023. *Regional Energy Deployment System Model.*

55. New York State Energy Research and Development Authority (NYSERDA). 2022. *New York Great Lakes Wind Energy Feasibility Study*. NYSERDA Report Numbery 22-12. Renewable Energy Laboratory, Advisian Worley Group, and Brattle Group/Pterra Consulting.

56. Optis, M., Rybchuk, A., Bodini, A., Rossol, M. and Musial, W. 2020. *2020 Offshore Wind Resource Assessment for the California Pacific Outer Continental Shelf*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-77642.

57. Orsted. 2023. *Block Island Wind Farm.*

58. Orvis, R., Abhyankar, N., Lin, J., Kahrl, F., Yin, S., Paliwal, U., Liu, X., Khanna, N., Luo, Q., Wooley, D., O'Boyle, M., Ashmoore, O., Solomon, M., and Phadke, A. 2022. *Achieving an 80% carbon-free electricity system in China by 2035.* IScience, 25(10), 105180.

59. Pfeifenberger, J., DeLosa III, J., Bai, L., Plet, C., Peacock, C. and Nelson, R. 2023. *The Benefit and Urgency of Planned Offshore Transmission: Reducing the Costs and Barriers to Achieving U.S. Clean Energy Goals.* The Brattle Group.

60. Phadke, A., Paliwal, U., Abhyankar, N., McNair, T., Paulos, B., Wooley, D. and O'Connell, R. 2020. *2035: Plummeting Solar, Wind and Battery Costs can Accelerate our Clean Electricity Future;* Goldman School of Public Policy. University of California, Berkeley.

61. Phadke, A., Paliwal, U., Abhyankar, N., McNair, T., and Kirsey, J. 2021. *2035 Report 2.0: Plummeting Costs and Dramatic Improvements in Batteries Can Accelerate Our Clean Transportation Future*. University of California, Berkeley, California.

62. Port Esbjerg. 2023. *A world's first: Digital twin helps Port Esbjerg triple its wind capacity*.
63. Rand, J., Strauss, R., Gorman, W., Seel, J., Mulvaney Kemp, J., Jeong, S., Robson, D., Wiser, R. 2023. *Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection.* National Renewable Energy Laboratory.
64. Richards, H. 2021. *Offshore wind to revive 'hallowed ground' for U.S. steel - E&E News*. E&E News.
65. Shaner, M. R., Davis, S. J., Lewis, N. S., and Caldeira, K. 2018. *Geophysical constraints on the reliability of solar and wind power in the United States*. Energy & Environmental Science, 11(4), 914–925.
66. Shields, M., Marsh, R., Stefek, J., Oteri, F., Gould, R., Rouxel, N., Diaz, K., Molinero, J., Moser, A., Malvik, C. and Tirone, S. 2022. *The Demand for a Domestic Offshore Wind Energy Supply Chain*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-81602.
67. Shields, M., Stefek, J. , Oteri, F., Maniak, S., Kreider, M., Gill, E., Gould, R., Malvik, C., Tirone, S. and Hines, E. 2023. *A Supply Chain Road Map for Offshore Wind Energy in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-84710.
68. United Nations Intergovernmental Panel on Climate Change (UN IPCC). 2023. *Synthesis Report of the IPCC Sixth Assessment Report: Summary for Policymakers*.
69. United States Department of Agriculture (USDA). 2017. *Wind Energy Land Distribution In The United States of America*.
70. United States Energy Information Administration (EIA) Today in Energy. 2023. *More than half of new U.S. electric-generating capacity in 2023 will be solar.*
71. United States Geological Survey (USGSa). 2022. *Mineral Commodity Summaries 2022 - Iron and Steel*.
72. United States Geological Survey (USGSb). 2022. *How many turbines are contained in the U.S. Wind Turbine Database?*
73. Vineyard Wind. 2023. *Vineyard Wind 1.*
74. Way, R., Ives, M., Mealy, P. and Farmer, J. D. 2022. *Empirically grounded technology forecasts and the energy transition*. Joule.
75. Xu, M. 2023. Reuters. *China solar power capacity could post record growth in 2023*.