Wind Energy Needs Assessment

Prepared for the Maine Governor's Energy Office and the Maine Offshore Wind Roadmap

Date: November 2022

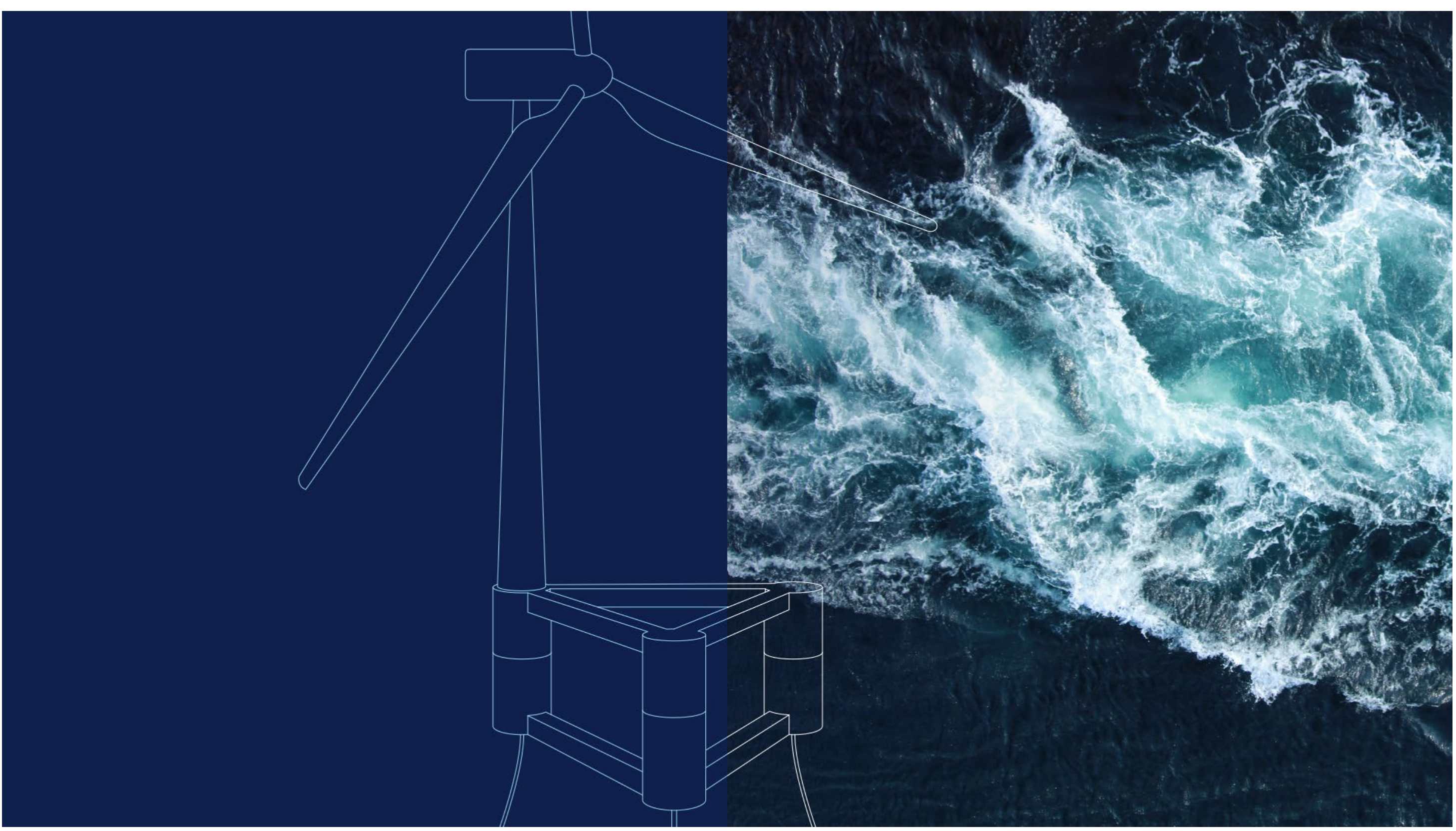

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Table 1-1. Abbreviations

Abbreviations	
ACP	Alternative Compliance Payment
ATB	Annual Technology Baseline
BOEM	Bureau of Ocean Energy Management
CAPEX	Capital Expenditures
CELT	Capacity, Energy, Loads, and Transmission
CHN	China
COD	Constrained Onshore Development
COP	Construction and Operations Plan
CRF	Capital Recovery Factor
CVA	Certified Verification Agent
DOE	Department of Energy
DNV	Det Norske Veritas
DP	Diverse Portfolio
DR	Demand Response
EDA	US Economic Development Administration
EERE	Office of Energy Efficiency and Renewable Energy
EFI	Energy Futures Initiative
EIA	Energy Information Administration
E3	Energy and Environmental Economics
ETO	DNV's 2021 Energy Transition Outlook
EUR	Europe
EV	Electric Vehicle
FCR	Fixed Charge Rate
FID	Final Investment Decision
FOM	Fixed Operation and Maintenance expense
GEO	State of Maine Governor's Energy Office
GHG	Greenhouse gas
IND	Indian Subcontinent
ISO-NE	New England Independent System Operator
LAM	Latin America
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelized Cost of Energy
LD	Legislative Document
MA	Massachusetts
ME	Maine
MEA	Middle East and North Africa
NAM	North America
NB Power	New Brunswick Power
NE	New England
NEAV	New England Aqua Ventus, LLC
NEB	Net Energy Billing
NECEC	New England Clean Energy Connect
NEE	North East Eurasia
NEPOOL	New England Power Pool
NREL	National Renewable Energy Laboratory
OETF	Ocean Energy Task Force
OPA	Organization of Economic Cooperation and Development Pacific

Abbreviations	
OPEX	Operating Expenditures
OSW	Offshore wind
PV	Photovoltaic
R&D	Research and Development
RECs	Renewable energy credits
REGMA	Renewable Energy Goals Market Assessment
RI	Rhode Island
RPS	Renewable Portfolio Standard
SAP	Site Assessment Plan
SEA	South East Asia
SSA	Sub-Saharan Africa
TRL	Technology Readiness Level
UK	United Kingdom
UOD	Unconstrained Onshore Development
US	United States
VOM	Variable Operation and Maintenance
VT	Vermont
WTG	Wind turbine generator

Table 1-2. Units

Units	
ft	feet
GW	Gigawatt
GWh	Gigawatt-hour
km²	Square kilometers
kW	Kilowatt
kWh	Kilowatt-hour
m	Meters
m/s	Meters per second
MW	Megawatt
MWh	Megawatt hour
Nm	Nautical miles
Sq mi	Square miles
TW	Terawatt
TWh	Terawatt hour
yr	Year
trn	Trillion
PJ	Petajoule

1 EXECUTIVE SUMMARY

Supported by a $2.166 million grant from the US Economic Development Administration, the Maine Governor's Energy Office is developing an Offshore Wind Roadmap (the "Roadmap") to grow Maine's overall economy and improve its economic resilience through the development of the offshore wind industry. The Roadmap is being developed by an advisory committee and four working groups with broad public input, focusing on energy markets and strategies, fisheries, environment and wildlife, supply chain, workforce development, ports, and marine transportation.

This offshore wind energy needs assessment aims to inform the Roadmap by developing scenarios to estimate offshore wind development in the Gulf of Maine under different potential future electricity demand and renewable supply conditions. This includes an assessment of the long-term (through 2050) renewable needs for New England and how offshore wind from the Gulf of Maine could meet Maine's needs as well as the rest of New England. This report builds on targets set in statute for Maine such as the requirement to achieve 80% renewable energy by 2030 and a goal of 100% by 2050, as well as analyses already conducted in the state through the Renewable Energy Goals Market Assessment (REGMA) [2] and the Maine Climate Council [3], providing a focused assessment of offshore wind.

The offshore wind scenarios developed in this assessment informs subsequent studies aimed at developing the Maine Offshore Wind Roadmap further, including a socioeconomic analysis of the offshore wind scenarios, strategies that will optimize the deployment of offshore wind in Maine in a way that maximizes its benefits to Maine people, and offshore wind transmission strategies.

1.1 Key takeaways

This analysis resulted in several clear takeaways that can inform the state of Maine as offshore wind is developed in the Gulf of Maine.

Maine's requirements established to fight climate change, passed with bipartisan support by the legislature, will necessitate substantial new renewable energy resources in the coming decades, both onshore and offshore in the Gulf of Maine. Based on this assessment, a future scenario under which Maine could achieve its requirements using onshore renewable energy alone is highly implausible.

To meet greenhouse gas reduction requirements, Maine and the other New England states will need to electrify key sectors of the economy, which will require new renewable generation to serve both existing usage and this growing electricity demand. Maine alone, if it chooses to allow unlimited land use for new onshore wind and solar generation and the associated transmission and other necessary infrastructure, could theoretically meet its renewable generation needs with onshore renewables, although such a scenario is highly implausible given the amount of transmission and land use required as well as the complimentary generation profiles of various renewable technologies. Facing reasonable constraints on onshore renewables development, Maine will need to generate between 9.3 and 12.4 TWh annually from offshore wind by 2050, corresponding to 2.1-2.8 GW of installed offshore wind generation capacity.

Other New England states are also pursuing a rapid transition to renewable electricity generation to meet growing electricity needs and fight climate change, and they are looking to large scale offshore wind in the Gulf of Maine to serve these needs.

Other New England states also have aggressive renewable portfolio standards, requiring the vast majority of their electricity generation to come from renewable resources by 2050. These states are planning for large amounts of offshore wind to help them meet these standards, including generation from the Gulf of Maine. The companies that bid in the federal auction for offshore wind leases in the Gulf of Maine starting in 2024 are likely to look to New England regional demand as they plan construction of offshore wind installations. Unless Maine pursues large-scale development of onshore renewables (including associated land use for installations and transmission) to export to the rest of New England, the region will need between 14.8 and 53.4 TWh generated from Gulf of Maine offshore wind by 2050, corresponding to 3.3 to 11.9 GW of installed generation capacity. Given this report does not analyze hourly demand, these estimates are lower than studies completed in other New England jurisdictions [51][52][53].

This analysis estimated annual renewable energy needs, but did not estimate the additional renewable generation capacity needed to meet hourly demand. Qualitative analysis shows that offshore wind is likely to prove complementary to other renewables, given its high generation profile at night and in the winter.

The need for offshore wind was based on first determining total annual need, and then determining how much renewable generation would match that total annual need. It did not examine whether this amount of generation would meet the need on an hourly level, which is necessary to ensure electric grid reliability. Deployment of energy storage technologies, for which the state of Maine has established additional goals, is a key consideration for meeting this need. The next step for refining this needs assessment would be to incorporate the comparison of hourly need and generation. Offshore wind in the Gulf of Maine, given its ability to generate at night (when there is no solar generation) and increased winter generation (when heating needs are greatest), may prove even more necessary when such an hourly analysis is completed.

DNV determined that offshore wind in the Gulf of Maine is most likely to be more than three miles off the coast, employ floating turbine technology, and take at least 7-9 years to develop and construct before providing electricity to the grid.

This analysis also established some basic assumptions around how offshore wind in the Gulf of Maine will be constructed, using DNV's deep experience with offshore wind development at the global level. Offshore wind in the Gulf of Maine is most likely to be more than three miles from the coast, in federal waters, and, because this is deep water, employ floating technology (as opposed to fixed-bottom turbines). It is most likely to take at least 7-9 years after federal leases are auctioned until offshore wind installations are delivering power to the grid, assuming the infrastructure for planning and construction are in place when needed. This timeline includes assumptions of five years of site assessment, environmental analysis, and planning (including BOEM approval of these steps), two years of BOEM reviews, and two years of fabrication, construction, and installation. This means that, given BOEM's stated timeline for the Gulf of Maine lease auction in 2024, the earliest that commercial offshore wind would be delivering power is approximately 2032, even with planning and preparation beginning soon.

With vast offshore wind generation potential in the Gulf of Maine, the State of Maine's primary challenge is to cultivate an environment that fosters the development of a floating offshore wind industry in Maine. This process should include policies and incentives that lower the levelized cost of energy (LCOE), attracting investment into Maine, while maximizing the benefits to Maine people. This challenge is the impetus for further studies for the Energy Markets and Strategies Working Group which evaluate the socioeconomic impacts of each of these scenarios, deployment strategies that maximize benefits to Maine, and transmission and land use strategies for floating offshore wind in Maine that ensure a balanced approach to serving Maine and the rest of the region.

1.2 Underlying offshore wind assumptions

In order to estimate the amount of Gulf of Maine offshore wind needs to meet the decarbonization requirements of Maine and New England, DNV first developed parameters around the projected regulatory environment, technology, development timeline, and the future cost for offshore wind. The conclusions in these areas are listed below and are used as assumptions throughout the analysis.

1. Offshore wind development in state waters (within three miles of the coast) will remain prohibited, so development will be exclusively in federal waters.
2. 100% of the technology deployed will be floating offshore wind turbines due to the characteristics and depth of the ocean floor in federal waters of the Gulf of Maine.
3. The maximum offshore wind generation that could be developed in the Gulf of Maine by 2030 is assumed to be 155 MW.[1] This is because the first leases for Gulf of Maine development are scheduled to take place in 2024, and permitting, planning, approvals, environmental review, construction, and installation are likely to take a minimum of seven years.
4. The LCOE for floating offshore wind will be cost-competitive with fixed-bottom offshore wind by the early 2030s [27].

1.3 Demand and supply scenarios

To model the amount of offshore wind needed in the Gulf of Maine to meet Maine and New England demand, DNV developed two demand projections and three supply scenarios.

1.3.1 Demand scenarios

As part of their decarbonization strategies, Maine and the other New England states are rapidly transitioning energy use to electrified technologies (electric vehicles, electric heat pumps, etc.), which will increase the amount of total electricity demand. The two demand projections for New England both reflect this demand increase, but the **base demand** scenario reflects a smaller increase than the **decarbonization demand** scenario. Both scenarios are based on prior analysis from the Synapse Energy Economics report for the Maine Climate Council [47]. The high decarbonization demand scenario is just under the highest two demand projections in the literature on New England decarbonization, and the base demand scenario is just above the lowest two demand projections (see Figure 1-1). Maine projected demand is the same in each scenario and reflects the estimate adopted by the Maine Climate Council.

Table 1-1 below shows the demand projections for New England through 2050 for each of the scenarios.

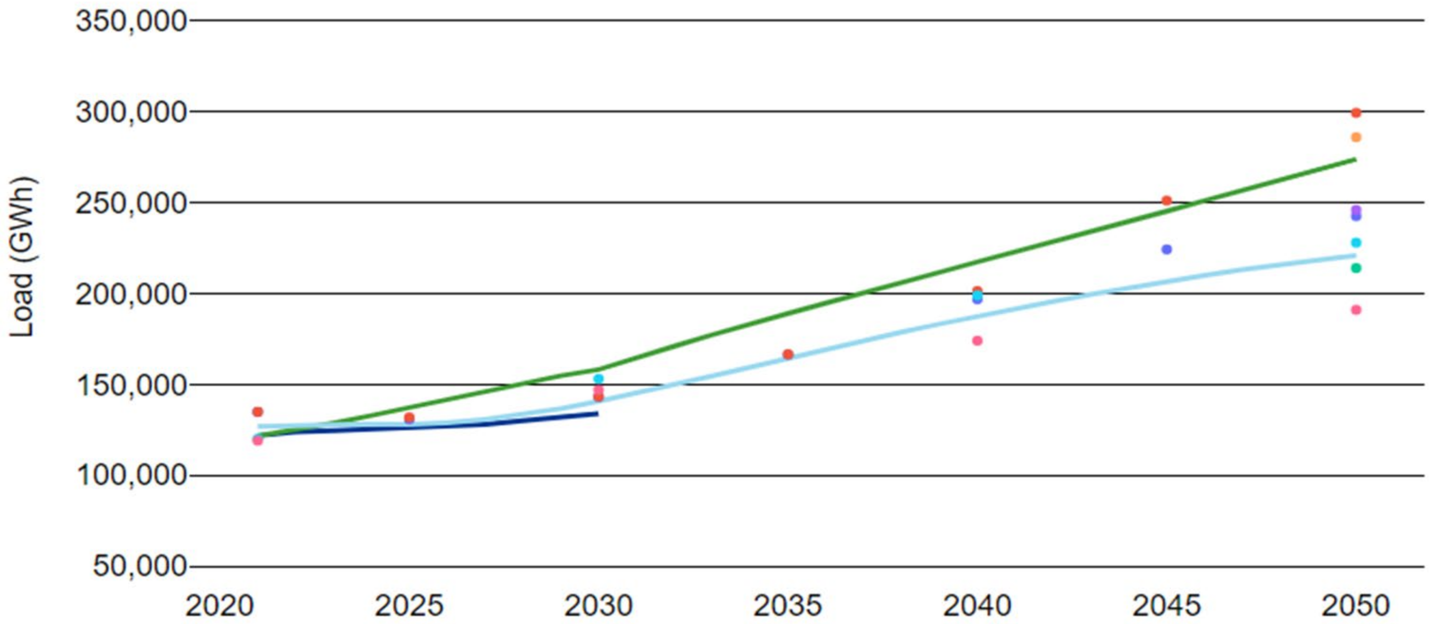
Table 1-1. Projections of demand for base and decarbonization demand scenarios

Year	Base demand projection (GWh)	Decarbonization demand projection (GWh)
2030	140,780	158,136
2040	187,503	217,336
2050	220,840	273,874

Figure 1-1 shows how the base demand and decarbonization demand scenario compare to other demand projections from the literature.

[1] Includes Gulf of Maine Floating Offshore Wind Research Array to be developed through a University of Maine collaboration with New England Aqua Ventus, LLC (NEAV), a joint venture between Diamond Offshore Wind and RWE Renewables. The state's first pre-commercial-scale floating offshore wind project expected to contribute Class 1A renewable energy credits (RECs). This analysis also includes the University of Maine's Aqua Ventus I single-turbine 11 MW demonstration project (the Monhegan project).

Figure 1-1. Demand projections from this report's base and decarbonization scenarios, compared to other projections from the literature



- ISO NE, 2021 CELT report
- Synapse Energy Economics report for Maine Climate Council, Maine Scenario 4 projections scaled to New England based on population and relative energy intensity
- Synapse Energy Economics report for Maine Climate Council, New England Scenario 1 projections
- Evolved Energy, 2020 Energy Pathways to Deep Decarbonization Report, All Options Scenario
- Evolved Energy, 2020 Energy Pathways to Deep Decarbonization Report, All Options Scenario including Electrolysis and Electric Boilers
- Brattle Efficiency
- Brattle Electrification
- Brattle Electrification + H
- E3 EFI High Electrification

1.3.2 Supply scenarios

DNV designed three supply scenarios to explore how land-based transmission constraints and renewable energy development costs will affect onshore and offshore renewable development in Maine and the Gulf of Maine. For future renewables expansion, we only consider the options of solar and wind, and do not consider new large-scale hydro, nuclear, biomass, etc. This is based on the cost limitations and other constraints described in the REGMA [2]. The three supply scenarios all assume that the New England Clean Energy Connect project is built and operational, and are as follows:

1. **Constrained onshore development (COD) Scenario: Northern Maine line built, no additional onshore transmission in Maine.** In this scenario, Maine's onshore renewable generation (onshore wind and solar) is limited to distributed solar and those solar, wind, and transmission projects currently in the development pipeline. This assumes that the transmission line per Legislative Document (LD) 1710[2] is built, enabling approximately 1,200 MW of additional renewable generation, plus another 793 MW to satisfy other projects in the pipeline, for a total of 1,993 MW. However, no additional transmission to northern or western Maine is constructed, meaning that no additional land is needed for this purpose.
2. **Unconstrained onshore development (UOD) Scenario: Unconstrained resource selection with unconstrained onshore development and aggressive offshore wind cost reduction**. In this scenario, the aggressive projections of decreasing LCOE for offshore wind make it more competitive with onshore resources, but no constraints are placed on transmission or land use for onshore resources. This scenario assumes the transmission line per LD 1710 is built, along with any other needed transmission for offshore and onshore development.
3. **Diverse Portfolio (DP) Scenario: *Constrained onshore development* scenario with additional onshore transmission.** This scenario incorporates elements of both the *constrained* and *unconstrained onshore development* scenarios, assuming the same aggressive projections of decreasing LCOE for offshore wind. This scenario is not as conservative as the constrained onshore development scenario (which assumes 1,993 MW of new transmission). Instead, it assumes the potential to develop moderate additional onshore transmission (and the associated land) enabling up to 3,000 MW of additional onshore wind and/or solar generation located in Maine.

This resulted in six scenarios used to model the offshore wind needed in the Gulf of Maine to meet Maine and/or New England's demand for renewable energy.

Table 1-2. Matrix of demand and supply scenarios

		Supply		
		Constrained Onshore Development	**Unconstrained Onshore Development**	**Diverse Portfolio**
New England Demand	Base Case Demand	1	3	5
	Decarbonization Demand	2	4	6

1.4 Key results

The model results include separate results for the amount of Gulf of Maine offshore wind necessary to meet:

1. The state of Maine's renewable energy needs

[2] The Maine Legislature passed LD 1710 in 2021, which established the Northern Maine Renewable Energy Development Program which could result in approximately 1,200 MW of new onshore renewable energy resources in northern Maine and associated transmission infrastructure.

2. New England's regional renewable energy needs

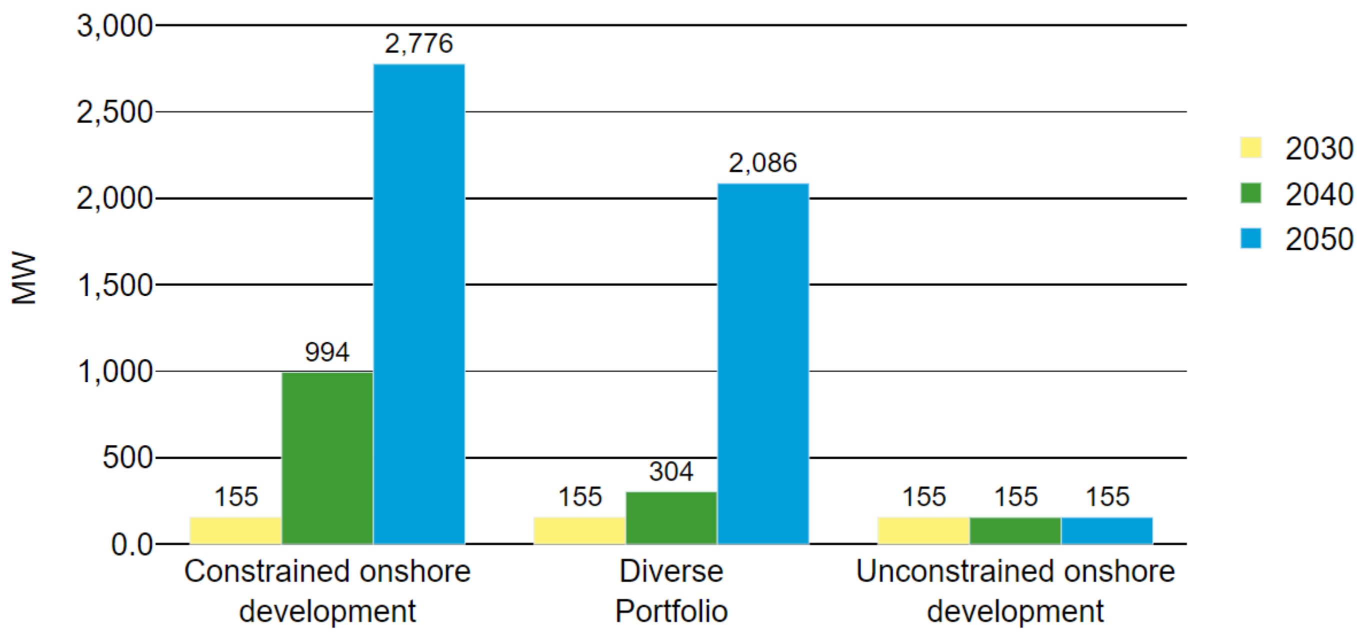
The generation to fill all of New England's need represents the potential for Gulf of Maine offshore wind to meet the regional demand, after other existing and planned renewable development, including other offshore wind, has been accounted for.

These results come from a process in which the least-cost renewable resources are chosen every year, given the total potential for onshore resources in Maine and offshore wind in the Gulf of Maine. The resource amounts are also limited by transmission constraints, as specified in the scenario descriptions above. This analysis examines the resources to meet the net annual renewable need in both Maine and New England but does not determine how to meet needs at the hourly level, which would likely be greater due to resource intermittency and other factors.

1.4.1 Maine results

The scenarios reflect offshore wind projections for Maine in 2030, 2040, and 2050 as depicted in Figure 1-2. below, each meeting Maine's requirement of 80% renewable energy by 2030 and a goal of 100% renewable energy by 2050.

Figure 1-2. Offshore Wind projections for Maine scenarios (2030, 2040, 2050)



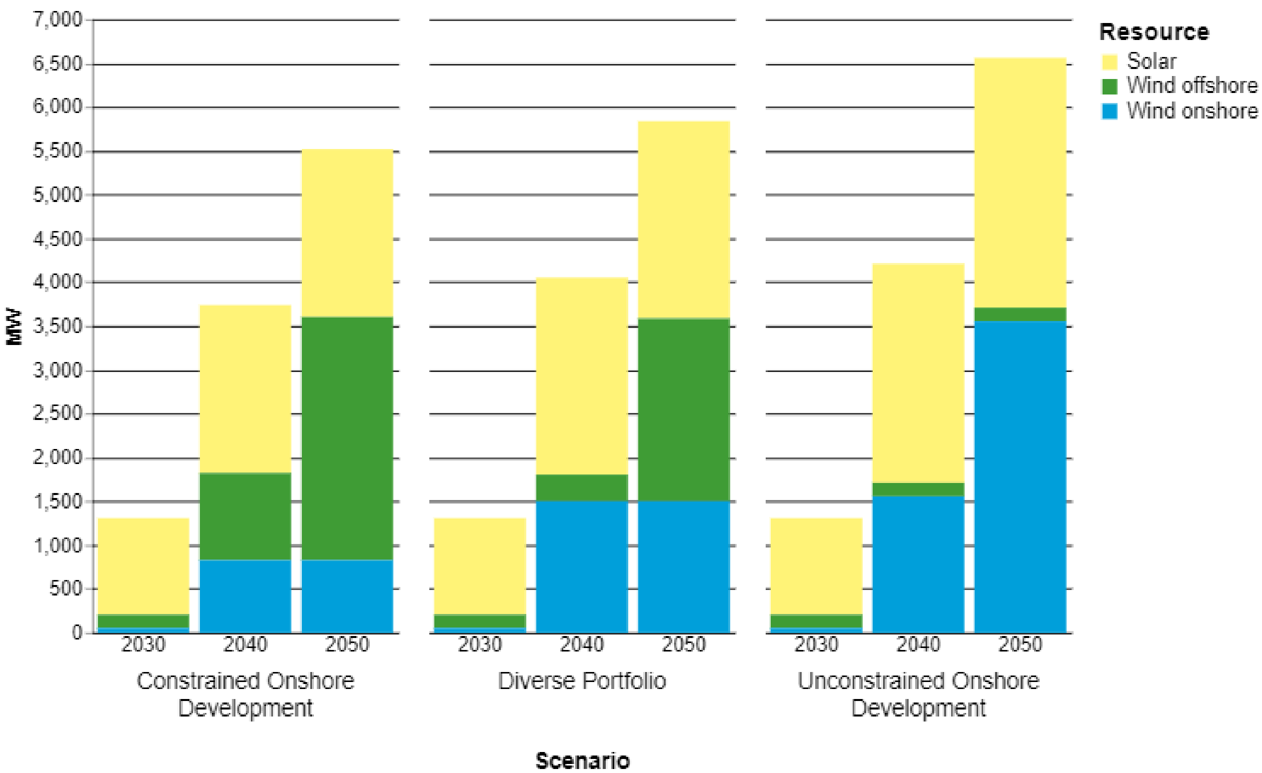
Based on the results of Maine in-state demand, DNV makes the following observations regarding offshore wind development:

- Offshore wind generation serving Maine is expected to be the highest (total of 2,776 MW by 2050) under the Constrained Onshore Development scenario, where onshore renewable resources are most constrained by transmission (no additional transmission or associated land use beyond LD 1710).
- If transmission (and associated land use) is unconstrained for onshore renewable resources, as in the Unconstrained Onshore Development scenarios, then offshore wind generation serving Maine is expected to be limited to the 155 MW offshore wind research array and Monhegan project, as even aggressive (10-25%) cost reductions to floating offshore wind do not currently compete with less costly onshore wind and solar. In this scenario, by 2050, Maine builds large amounts of additional solar (2,850 MW) and onshore wind (3,550 MW) to serve in-state demand.
- Even if transmission capacity is increased from the Constrained Onshore Development scenario to 3,000 MW onshore, onshore renewable resources remain constrained, leaving more need for offshore wind to fill Maine's requirement for

renewable resources. This Diverse Portfolio scenario thus results in a more evenly-balanced set of renewable energy resources, both onshore and offshore, which has the potential to contribute both to resiliency and meeting hourly demand, though more research is needed on how different resource mixes would affect both of those goals.

Except in the Unconstrained Onshore Development supply scenario, projections anticipate that the development of Maine's onshore renewable resources will be limited by the land use requirements and other challenges of transmission expansion. Thus, these scenarios see the amounts of solar photovoltaic (PV) and onshore wind scaled to each scenario's transmission constraints. Higher-cost floating offshore wind fills the remaining shortage of renewable energy. Under the Unconstrained Onshore Development supply scenario, despite aggressive reductions in the LCOE for floating wind, solar PV and onshore wind are expected to remain the lowest-cost resource serving Maine. Figure 1-3 shows Maine resource projections for each supply scenario in 2030, 2040, and 2050 respectively.

Figure 1-3. Maine resource projections for each demand scenario



1.4.2 New England results

The New England results show the amount of Gulf of Maine offshore wind modeled to meet the needs of the wider New England region. Because of the time needed for preparation and construction, this analysis assumes that by 2030 there will be no operational offshore wind in the Gulf of Maine beyond the research array and the Monhegan project. Figure 1-4 and Figure 1-5 show the amount of operating Gulf of Maine offshore wind projected in each of the scenarios in 2030, 2040, and 2050, highlighting in lighter blue the amount needed to satisfy Maine's projected demand. The remaining offshore wind (dark blue) would provide renewable energy to the rest of New England. In the base case demand scenarios, New England's needs are met with offshore wind development that is between 17 and 34 percent of the total estimated amount that could be built by 2050 (20 GW). In the high decarbonization scenarios, however, a much larger percentage of that maximum is built – between 39 and 60 percent.

Figure 1-4. Base demand scenario: Gulf of Maine offshore wind projections serving Maine and the rest of New England

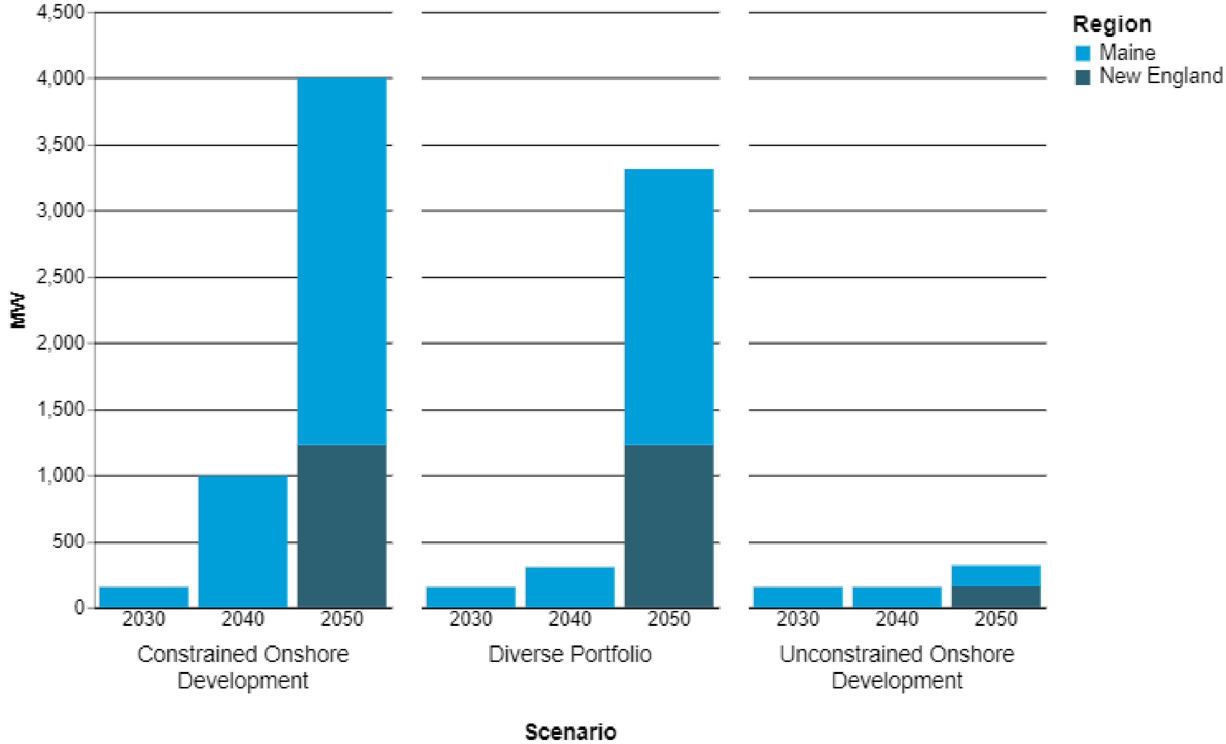


Figure 1-5. Decarbonization demand scenario: Gulf of Maine offshore wind projections serving Maine and the rest of New England

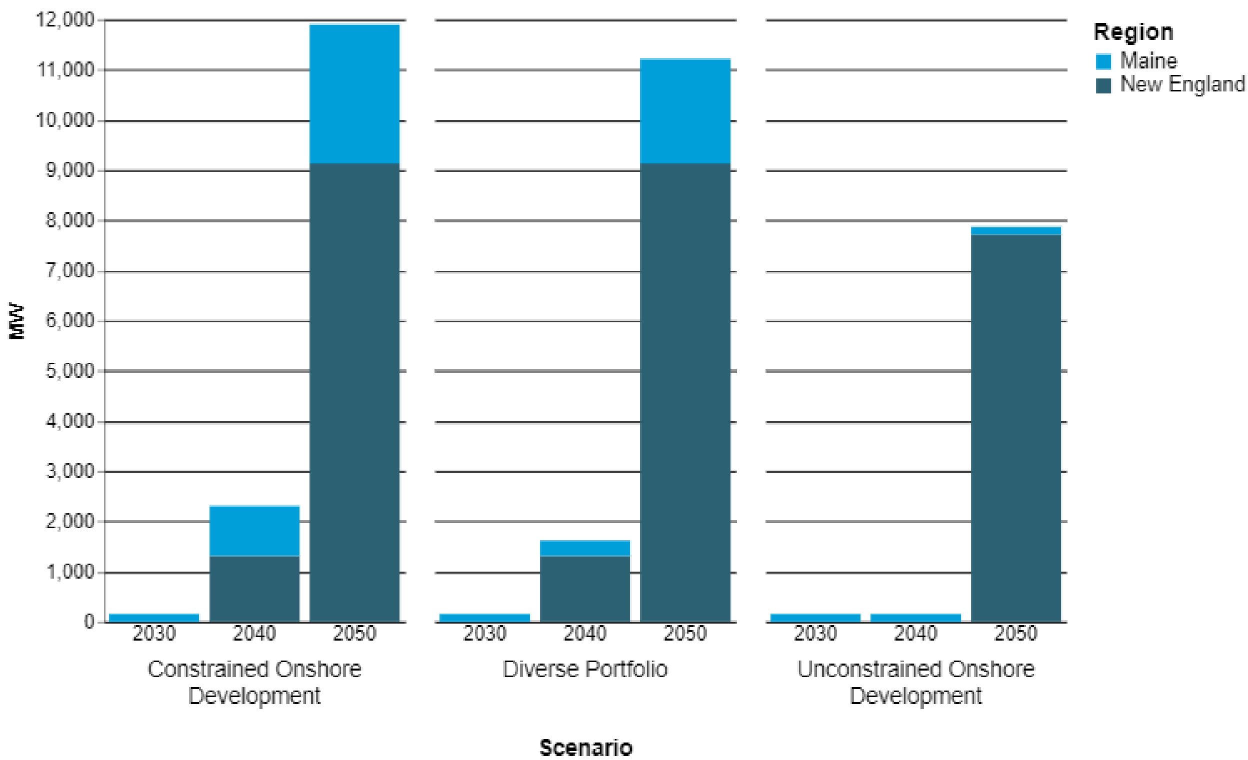


Figure 1-6 and Figure 1-7 show the Maine-supplied renewable generation mix projected for each New England scenario in 2030, 2040, and 2050. These graphs include the amount of new renewable generation from Maine and the Gulf of Maine for all-New-England needs. Offshore wind comprises between 48 and 81 percent of the total new Maine-based renewable generation predicted in 2050. The highest amount is in the constrained onshore development decarbonization demand scenario (about 53,000 GWh from 11.9 GW installed) and the lowest amount is in the unlimited onshore development base demand scenario (about 15,000 GWh from about 3.4 GW installed). In this latter scenario, the demand for electricity at the New England level that cannot be met locally is served by additional onshore wind and solar construction in Maine, which would involve additional transmission construction and land use.

Figure 1-6. Base demand scenario: New England resource projections

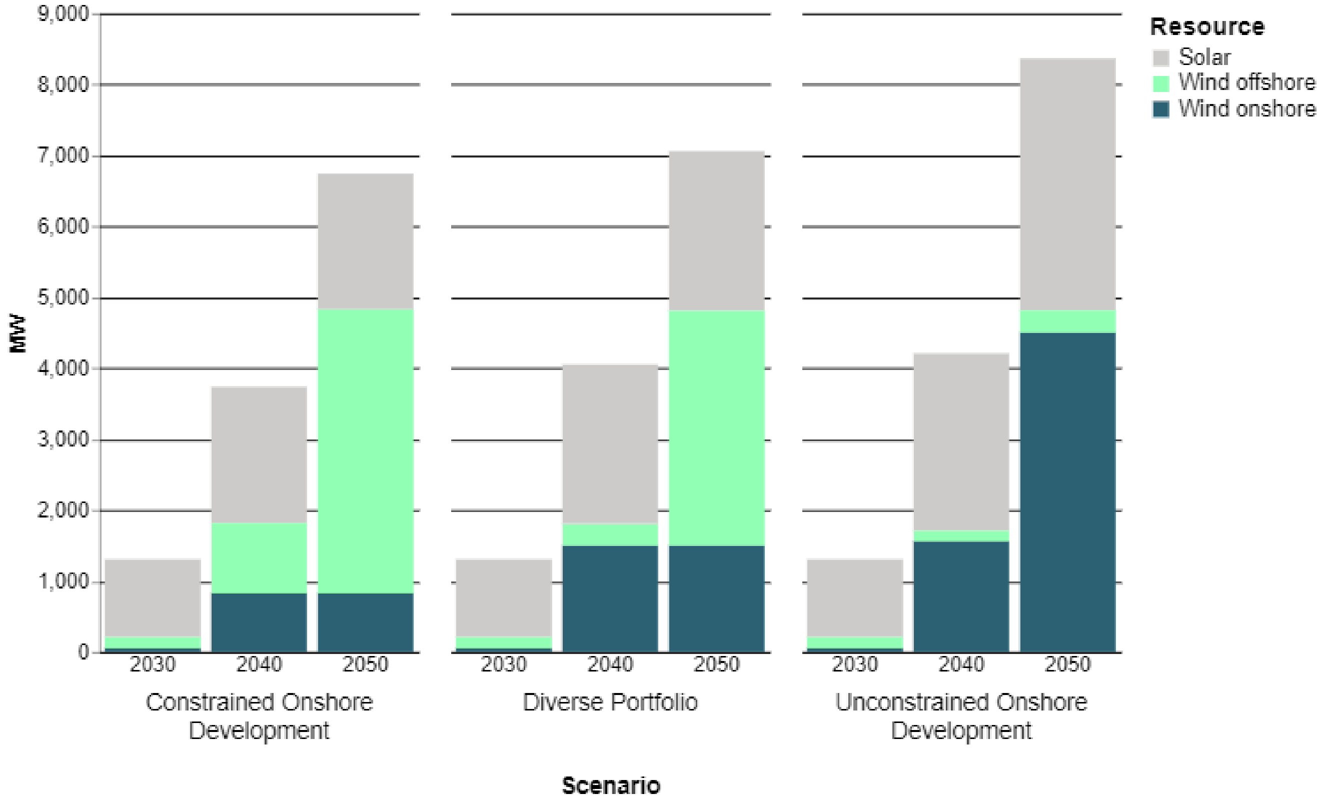
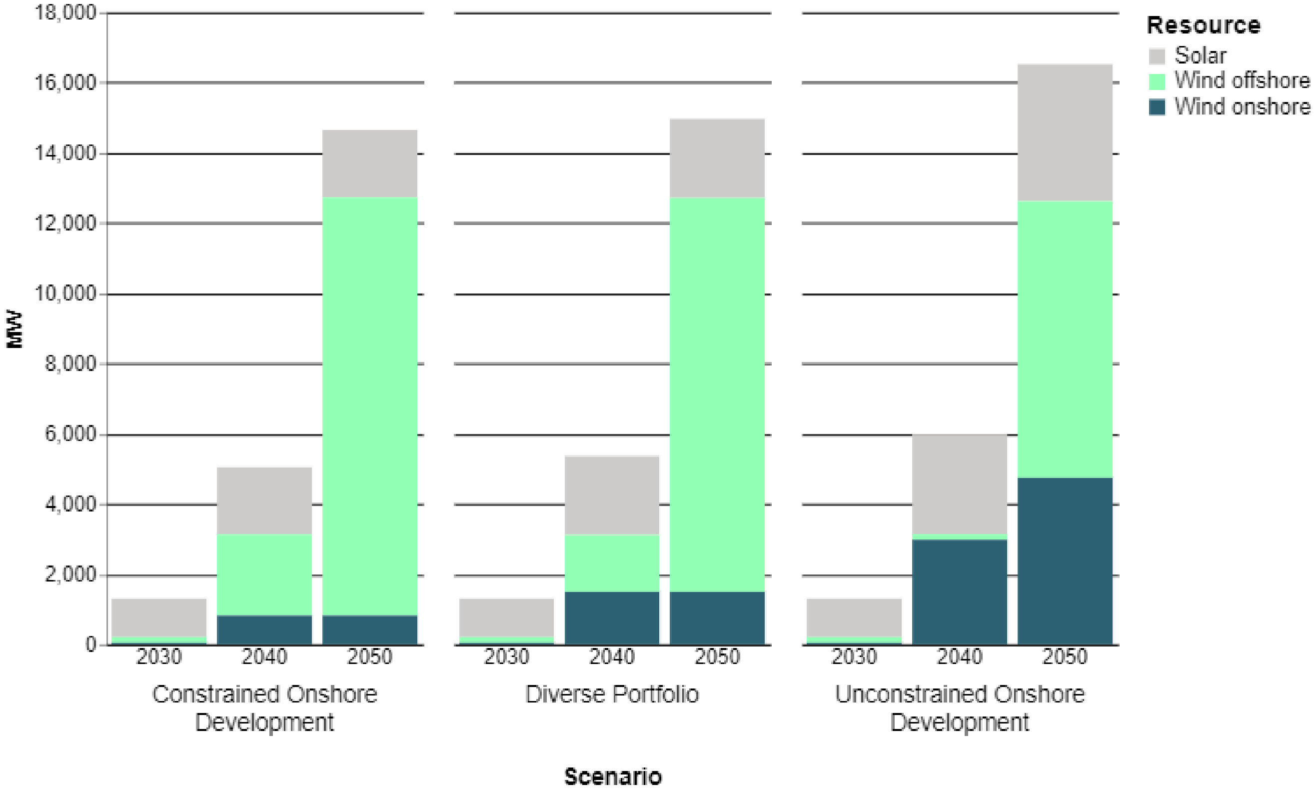


Figure 1-7. Decarbonization demand scenario: New England resource projections



1.5 Future research and limitations

This work is just one step in the continuing research on offshore wind needs that will need to be conducted as New England decarbonizes. Future work will need to take into account new developments as well as elements that this research did not address. The first of these is the need for electricity supply to meet demand in real time. Whereas this study only considers meeting the total annual need from total annual renewable generation, as the region increases the fraction of electricity demand served by renewables, the real-time ability of these renewable resources to serve need will be critical. This will involve assessing how demand is likely to vary throughout the year, how that variation might change, and how it might be different in different years. The same analysis will be necessary on the generation side. These analyses will need to be compared to help determine the best mix of renewable generation types. This comparison will also yield information to allow for the construction of a reliable grid that meets capacity requirements.

Additionally, this analysis does not address energy storage and its potential roles and limitations in grid and load management. The costs, limitations, strengths, and weaknesses of different storage technologies, and the costs and benefits of choosing storage versus additional generation, should be examined. Hydrogen production is also not discussed in this report. While not an economical storage solution at the time of this report, the need for and complexities around producing hydrogen may need to be considered in the future.

This research estimates the offshore wind and other renewables need at discrete time points (2030, 2040, and 2050) to meet the continuously growing need for additional electricity. However, renewable generation is built in a stepwise fashion: as each additional project becomes operational, generation will increase by the full capacity of the project all at once. As projects are developed and the size of each development is better understood, this stepwise character of adding generation can be added to needs modeling.

Finally, the inputs used in this model, including demand projections and costs of renewable generation (especially for floating offshore wind) are all uncertain. Future work should update this data frequently to give an ever-more-accurate prediction of the future.

1.6 Organization of report

The body of this report gives detailed explanations of the methods, results, and conclusions presented in this executive summary. Section 2 describes the background and context for the study, and its ultimate objective, and provides an outline introducing the contents of the report. Section 3 describes the scenario development process and the key assumptions underlying the scenarios. Section 4 describes the data sources used as model inputs, including the offshore wind development potential, total renewable energy supply, and total demand for renewable energy in Maine and the New England region. Section 5 presents detailed results for each scenario. Section 6 synthesizes the results to inform Maine's offshore-wind-related decisions, enabling the Roadmap working groups and advisory committee to weigh the tradeoffs of energy-related decision-making and shape effective public policy around offshore wind.

2 INTRODUCTION

2.1 Background and context

The State of Maine is committed to combatting climate change, advancing clean energy and energy efficiency, and growing the state's clean energy industry. In 2019, with bipartisan support, Governor Mills signed into law greenhouse gas (GHG) emissions reduction requirements of 45% from 1990 levels by 2030 and 80% by 2050. Furthermore, through LD 1429, An Act To Achieve Carbon Neutrality in Maine by the Year 2045, Governor Mills and bipartisan majorities in the legislature committed the state to carbon neutrality by 2045. In 2019, the governor also signed bipartisan legislation to increase Maine's Renewable Portfolio Standard (RPS) to 80% renewable energy by 2030 and a goal of 100% by 2050 [1].

To design a plan to meet these climate requirements, the State legislature also created the Maine Climate Council, an assembly of scientists, industry leaders, bipartisan local and state officials, and engaged citizens to develop a four-year plan to put Maine on a trajectory to achieve its ambitious emissions reduction targets. In December 2020, the Maine Climate Council released *Maine Won't Wait, A Four-Year Plan for Climate Action* [3]. One recommendation of the climate action plan is to ensure an adequate affordable renewable energy supply for Maine by identifying achievable targets for the cost-effective deployment of clean energy generation technologies, including offshore wind [3].

The state's 10-year Economic Development Strategy calls offshore wind a prime opportunity for growing Maine's economy. It encourages a balanced agenda for offshore wind that maximizes economic benefits for Maine people while creating a culture of innovation that gives Maine a leadership position in an industry expected to generate $1 trillion in global investment by 2040 [4]. The State's Economic Recovery Plan, designed to respond to the impacts of the COVID-19 pandemic on Maine's economy and people, released in November 2020, calls for investing boldly, strategically, and consistently in next-generation technology and innovation, including in offshore wind energy, to grow Maine's value-add economy [5].

To assess potential pathways to meet the RPS, the Governor's Energy Office (GEO) released a 10-year Renewable Energy Goals Market Assessment (REGMA) in February 2021, which includes an analysis and review of the opportunities, potential, and challenges facing Maine in reaching its 80% RPS by 2030 [2]. The study highlights offshore wind as well-positioned to help Maine achieve its renewable energy goals in the coming decades [2].

Through the Maine Offshore Wind Initiative (the "Initiative"), launched by Governor Mills in 2019, the state is exploring opportunities for thoughtful development of offshore wind energy in the Gulf of Maine and is determining how to best position Maine to benefit from a rapidly growing industry while ensuring the sustainability of Maine's coastal heritage, existing ocean users, and environment [4].

In October 2020, the U.S. Economic Development Administration (EDA) awarded a $2.166 million grant to the GEO to advance the offshore wind industry in Maine through the development of a comprehensive industry Roadmap [6]. The Roadmap, as part of the overall Initiative, is being developed through a collaborative stakeholder engagement process while taking a holistic approach to advancing the offshore wind economy in the Maine state [7]. The Initiative includes developing strategies that realize potential economic benefits in areas such as ports and infrastructure, manufacturing and supply chain, and workforce development. The effort also focuses on planning and data-gathering to support siting decisions, to minimize potential effects on the environment, coastal communities, and fisheries [7].

The Initiative builds on more than a decade of analysis, research and development, and policy efforts in Maine. More than 14 years ago, Maine took bipartisan steps to recognize the opportunity for offshore wind development to reduce dependence on imported fossil fuels and create short and long-term economic and employment benefits for Maine citizens [1].

In 2008, the Ocean Energy Task Force (OETF) was launched to review opportunities for offshore wind in Maine. The final report released in 2009 recommended that "Maine make a major commitment to preparing the way for the development of its offshore wind, tidal, and wave power" and set forth ambitious offshore wind targets [8]. In April 2010, in response to the report of the OETF, the Legislature enacted the Ocean Energy Act with unanimous support in the House and the Senate, setting Maine's first offshore wind goals and promoting research for the commercialization of ocean energy resources. In September 2012, the University of Maine published the Maine Deepwater Offshore Wind Report examining economics and policy, electrical grid integration, wind and wave, bathymetric, soil, and environmental research [9]. The efforts of the Roadmap and this wind energy needs assessment build on that work and ensure that existing data, resources, and targets are both informed by past research and refined to meet contemporary demands and opportunities.

2.2 Objectives

This report provides an assessment of how offshore wind in the Gulf of Maine can contribute to filling both Maine and New England's long-term renewable energy needs. This builds on the targets set in statute and analyses already conducted in the state, including the REGMA (which provides existing models to project renewable energy needs through 2050) and the Maine Climate Council. It summarizes and considers regional targets and energy needs with modeling based on the best available data to identify specific offshore wind targets between now and 2050.

The key objectives of this report are to:

1. Consider the potential for floating or other deep water offshore wind in the Gulf of Maine
2. Determine how offshore wind can contribute to meeting the state and neighboring regions' renewable requirements, including accounting for load increases due to strategic electrification.

2.3 GEO's role

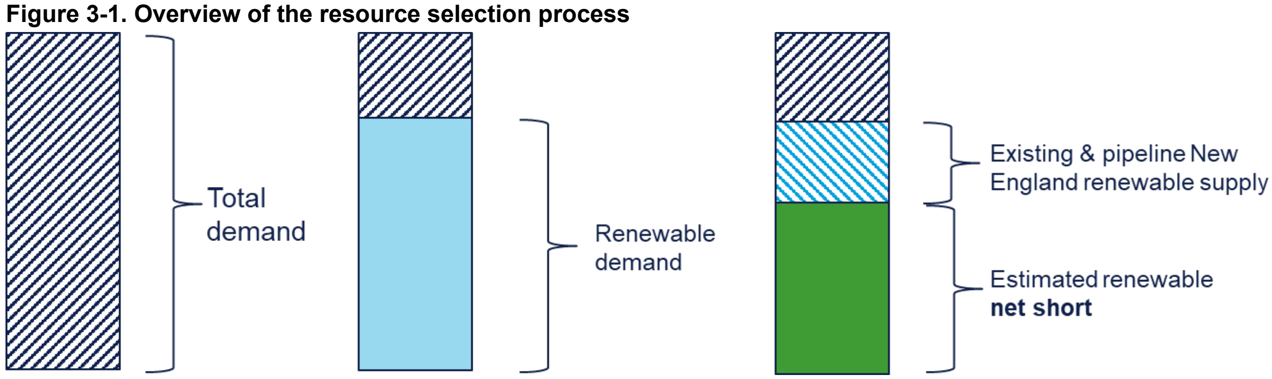
The GEO is the sponsor of this study and selected DNV to conduct this work. GEO worked with DNV and members of the Maine Offshore Wind Roadmap Energy Markets and Strategies working group to design the study, conduct public comment processes, facilitate and participate in meetings between stakeholders and consultants, and prepare this report. The information in this report was prepared by DNV and does not constitute an endorsement or recommendation by GEO, the State of Maine, or the Energy Markets and Strategies working group.

3 PROCESS OVERVIEW

This section outlines the scenario development process completed by DNV that modeled Maine and New England's offshore wind energy needs. This analysis builds upon targets set in statute and analyses already conducted in Maine through the REGMA and the Maine Climate Council. More detailed descriptions of the process and the data used can be found in Section 4. Specifically, Table 4-2 summarizes the various primary data inputs and how they were used in the model.

In this process, DNV first collected the best available data to determine the difference between projections of total renewable energy generated and total demand for renewable energy. This delta represents the remaining renewable supply shortage, or renewable net short, in each year and geography. This was modeled for 2030, 2040, and 2050, separately for both Maine and New England. The resource-selection model then determined the extent to which Maine's remaining renewable resources, including offshore wind, could fulfill this renewable net short. Renewable resources were selected based on cost (see Section 3.2.4), with the least cost remaining resource selected until the total demand was served or no potential renewable resource capacity remained. Figure 3-1 depicts the resource selection process used in the model.

Figure 3-1. Overview of the resource selection process



A key decision in this scenario modeling was whether to examine only annual net amounts of supply and demand (i.e., meeting net demand through net renewable generation) or whether to examine how supply could meet demand on an hour-by-hour basis over the year. Given that the whole New England region is undergoing deep decarbonization, understanding the likelihood of having renewable supply during a given hour, no matter the season or time of day, will be important for planners to consider. For example, solar is not available at night, but wind speeds tend to be higher at night. Offshore wind speeds are higher during the winter months, but certain regions can experience wind lulls.

However, selecting the mix of renewable resources and storage that would be needed to meet hourly demand is outside the scope of this study.[3] Therefore, this assessment focuses on net annual renewable energy requirements. While the modeled results do not address hourly needs, APPENDIX C includes data visualizations and qualitative descriptions that give a general sense of relative hourly supply and demand. This analysis does not calculate peak renewable demand shortages or the resources necessary to meet them.

3.1 Scenario development

DNV considered two demand projections and three supply scenarios to model the amount of offshore wind needed in the Gulf of Maine to meet Maine and/or regional demand.

3.1.1 Demand projections

DNV estimated two geographic levels of demand for this report: Maine-only and total New England. For Maine, the demand modeling adopted by the Maine Climate Council in "Maine Won't Wait" was assumed as Maine's projected electric demand

[3] The State of Maine is exploring the role of storage in its renewable energy initiatives.

through 2050 [3]. DNV assumed that Maine would meet its renewable portfolio standard requirement of 80% in 2030 and goal of 100% in 2050 and interpolated a 90% milestone for 2040. These percentages were multiplied by the total projected demand to yield total renewable demand.

For New England, DNV developed two demand projections, both of which include significant emissions reduction efforts. These were designed to represent the high and low ends of the range of demand projections in the literature. Both were based on the same source as Maine–Synapse Energy Economics' report for the Maine Climate Council–with different assumptions about how that demand would scale to the New England level [47]. DNV then estimated the renewable demand requirement percentage for New England using a weighted average of every state's renewable portfolio standard percentage, where the weights are that state's share of New England energy consumption.[4] Multiplying this percentage by total demand in each scenario-year yielded total renewable demand for New England by year. The renewable demand projections for each of the scenarios are shown in Table 3-1.

Table 3-1. Projections of renewable demand for Base Case and Decarbonization scenarios

Year	Base Case Renewable Demand Projection (GWh)	Decarbonization Renewable Demand Projection (GWh)
2030	140,780	158,136
2040	187,503	217,336
2050	220,840	273,874

3.1.2 Current and future expected renewable supply

To estimate supply needs for Maine and New England, DNV compared the total projected renewable demand to the already existing and projected renewable generation in the region, as shown in Table 3-2. All future Maine generation was not included in this step, but instead modeled later in the process (i.e., current energy procurements and programs in statute in Maine, as well as any potential generation not yet planned were included as part of the model output).

Table 3-2. Current and expected renewable supply

Region	Period	Source	Use in Model
Maine	Existing 2021	EIA	Subtracted from renewable demand to get renewable net short
Maine	New 2022-2050	--	Output
New England outside Maine	Existing 2021	EIA	Subtracted from renewable demand to get renewable net short
New England outside Maine	New 2022-2050	ISO NE 2050 transmission study	Subtracted from renewable demand to get renewable net short

Existing Maine and New England generation was obtained from EIA data [28]. Projected offshore wind generation in New England outside of Maine was taken from other states' plans for this resource. Other projected renewable generation in

[4] Renewable portfolio standards used are those from the REGMA with updates as described in Section 4.2.1.

these states was taken from the ISO NE 2050 Transmission Study [59]. Renewable imports were taken from the 2021 ISO NE Net Energy and Peak Load by Source file [60].

3.1.3 Estimating renewable net short

The renewable net short is the total renewable need after subtracting the existing and projected renewable energy supply estimates described above. The total need, renewable need, renewable supply, and the remaining renewable net short are defined below and then shown in Table 3-3 through Table 3-5 for the Maine and New England demand scenarios.

- **Total need** – The total power needs to meet the projected demand
- **Renewable need** – Total renewable energy power needed based upon the combination of total need and renewable portfolio standards established by Maine and other New England states
- **Existing and expected non-Maine renewable supply** – Existing renewable energy supply and imports for both Maine and the New England region, as well as projections of renewable energy for New England states (aside from Maine; additional renewable resources in Maine are the model output)
- **Renewable net short** – The remaining renewable energy need not met by the existing and expected non-Maine renewable supply. The model can fill this need with potential Maine resources up to the capacity potential (Table 3-6). As the goal of this report is to determine the extent to which Maine resources (specifically offshore wind) can serve Maine and New England's needs, the model can only select Maine resources.

Table 3-3. Demand by year (TWh) - New England – Base Case Scenario

NE – Base Case	2030	2040	2050
Total Need	140.8	187.5	220.8
Renewable Need	60.8	95.8	147.5
Existing & Expected Renewable Supply	74.9	94.6	123.4
Renewable Net Short	-14.1	1.2	24.1

Table 3-4. Demand by year (TWh) - New England - Decarbonization Scenario

NE - Decarbonization	2030	2040	2050
Total Need	158.1	217.3	273.8
Renewable Need	68.3	111.1	182.9
Existing & Expected Renewable Supply	74.9	94.6	123.4
Renewable Net Short	-6.6	16.5	59.5

Table 3-5. Demand by year (TWh) – Maine projections

Maine	2030	2040	2050
Total Need	15.6	22.9	28.6
Renewable Need	12.5	20.6	28.3
Existing & Expected Renewable Supply	9.450	9.450	9.450
Renewable Net Short	2.47	10.60	18.58

3.1.4 Supply scenarios

DNV developed three supply scenarios, incorporating feedback from GEO and the Energy Markets & Strategies working group. In each scenario, the model chose from Maine-based onshore wind, onshore solar, distributed onshore solar, and offshore wind to fill the renewable net short in both Maine and New England. Other resources, such as hydropower, biomass, etc. were not included as options for additional development given their relatively high cost and limited availability, as described in the State of Maine REGMA [2].

DNV assumed the total potential renewable energy capacity for each Maine-based resource as outlined in Table 3-6. Except for offshore wind, these capacities are based on numbers from the State of Maine REGMA [2]. This prior research incorporates land use and transmission limitations, which are applied in the current analysis of the supply scenarios. DNV independently assessed the potential for floating offshore wind capacity by year, primarily based on regulatory timing, technology maturity, construction time constraints, and development patterns seen in areas with more mature offshore wind markets.[5] Table 3-6 shows the total cumulative new development (baseline 2021) assumed possible in Maine for a given year, by resource. In 2050, 20 GW is the maximum cumulative new offshore wind development possible in the Gulf of Maine after 2021.

Table 3-6. Assumed Maine maximum capacity potential by resource by year (GW)

Year	Wind onshore new	Wind offshore	Solar PV	Distributed solar
2030	5	0.155	7	1.475
2040	5	5	7	1.475
2050	5	20	7	1.475

Other resources, including RECs, were not included in the choice set, as the State of Maine REGMA found these resources would either be extremely limited in additional capacity and/or more expensive than the resources used here.

DNV developed three supply scenarios:

1. **Constrained Onshore Development (COD) Scenario: Northern Maine line built, no additional onshore transmission in Maine.** In this scenario, Maine's onshore renewable generation (onshore wind and solar) will be limited to distributed solar and those solar and wind projects currently in the development pipeline, with the assumption that transmission lines to accommodate more than this generation will not be built. This scenario assumes that the transmission line specified by LD 1710 (June 2021), *An Act To Require Prompt and Effective Use of the Renewable Energy Resources of Northern Maine* [38] will be built, enabling approximately 1,200 MW of additional renewable generation in Aroostook County, in northern Maine, to be transmitted via the ISO-NE grid to load centers in the south. This scenario also assumes that another 793 MW of renewable generation will be constructed in southern Maine as a result of LD 1494, *An Act To Reform Maine's Renewable Portfolio Standard*. Together, these include 1,166 MW of new solar and 826 MW of new onshore wind resources, for a total of 1,993 MW. In this scenario, no additional transmission to northern or western Maine is constructed (beyond that enabled by LD 1710), restricting the amount of onshore renewable generation. No land use for additional transmission or onshore development is needed.
2. **Unconstrained Onshore Development (UOD) Scenario: Unconstrained resource selection with unconstrained offshore transmission and aggressive offshore wind cost reduction**. In this scenario, aggressive projections of levelized cost of energy (LCOE) for offshore wind make it more competitive with onshore resources, but no constraints are placed on transmission development or land use for onshore resources. This scenario assumes the transmission line per LD 1710 is built, along with any other needed transmission for offshore and onshore development.

[5] See APPENDIX A for more details on this process.

3. **Diverse Portfolio (DP) Scenario: Unconstrained Onshore Development scenario with additional onshore transmission.** This scenario incorporates elements of both the COD and UOD scenarios. It assumes the same aggressive cost reductions for offshore wind, as well as some onshore transmission restrictions. This scenario is not as constrained as the COD scenario (which assumes only 1,993 MW of new onshore resources), but rather assumes the development of moderate additional onshore transmission, with associated land use, to enable a total of 3,000 MW of additional onshore wind and/or solar generation located in Maine.

The assumptions for each of the six scenarios explored in this analysis are presented in Table 3-7.

Table 3-7. Matrix of demand and supply scenarios

Scenario No.	Demand Scenario	Supply Scenario	NE Demand	Additional Onshore Renewable Resources, Transmission Constrained	LCOE for Offshore Wind
1	NE Base Case	COD	Low	1,993 MW	Base case
2	NE Decarbonization	COD	High	1,993 MW	Base case
3	NE Base Case	UOD	Low	Unconstrained Transmission	Aggressive reductions (10-25%) to LCOE
4	NE Decarbonization	UOD	High	Unconstrained Transmission	Aggressive reductions (10-25%) to LCOE
5	NE Base Case	DP	Low	3,000 MW total	Aggressive reductions (10-25%) to LCOE
6	NE Decarbonization	DP	High	3,000 MW total	Aggressive reductions (10-25%) to LCOE

3.2 Underlying offshore wind assumptions

The key assumptions underlying the scenarios developed (per this Section 3) and modeled (per Section 5) are listed below in Table 3-8 and further explained in the subsections below.

Table 3-8 Underlying assumptions about offshore wind

1	**Policy:** There is a permanent moratorium for offshore wind development in Maine's state waters, so offshore wind serving Maine will be located in federal waters.
2	**Technology:** 100% of offshore wind generation serving Maine in federal waters will be floating technology.
3	**Timeline:** The planned 144 MW research array and the 11 MW Aqua Ventus I demonstration project will be the only Gulf of Maine offshore wind projects completed by 2030.
4	**Cost:** Floating offshore wind will be cost-competitive with fixed offshore wind by 2050

3.2.1 Maine policy

In July 2021, after hearing concerns from the fishing industry, Governor Mills signed into law LD 1619, which permanently prohibits new offshore wind projects in state waters [10]. The prohibition preserves State waters for recreation and fishing, where up to 75% of Maine's commercial lobster harvesting occurs, and codifies into law Maine's priority of locating offshore wind projects in federal waters in the Gulf of Maine. Regardless of the prohibition, DNV does not anticipate commercial development less than three miles off the coast given conflicts with fisheries, navigation, and viewshed concerns.

Assumption 1: There is a permanent moratorium for offshore wind development in Maine's state waters, so additional offshore wind serving Maine will be located in federal waters.

3.2.2 Offshore wind technologies in the Gulf of Maine

Offshore wind energy represents Maine's largest untapped natural energy resource, with more than 156 GW of potential energy in the Gulf of Maine. It is also a higher quality resource than onshore wind in the rest of Maine and most of the US [21]. Approximately 89% of the technical energy potential of the Gulf of Maine is in deep waters (> 60 m), ideal for floating offshore technology [21]. Additionally, the majority of the limited shallow water resource areas are within state waters, where offshore wind development is prohibited.

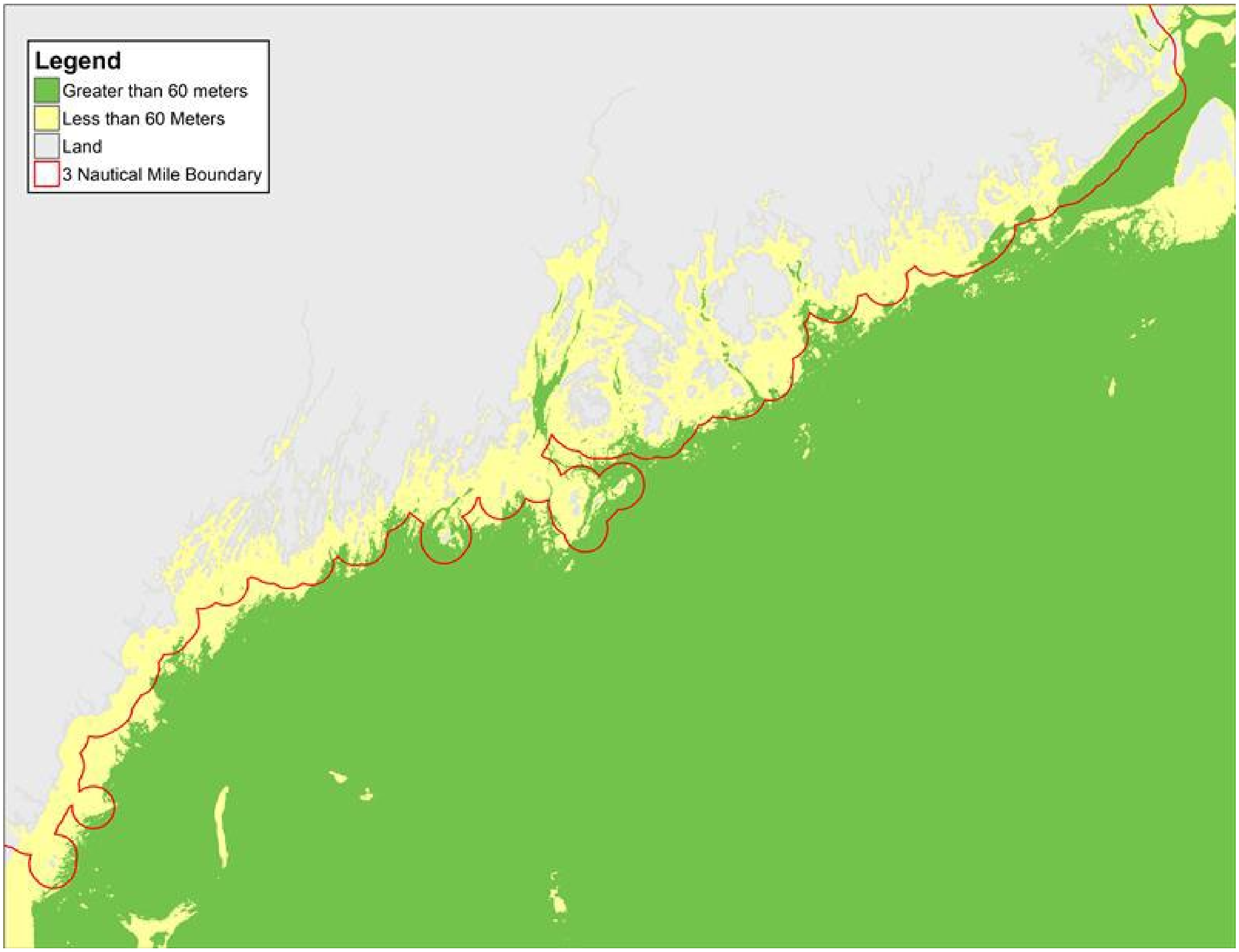
Table 3-9 shows the technical potential for wind resources in the Gulf of Maine, and Figure 3-2 shows the ocean depth along Maine's coast. Additional detail on technical potential and wind speeds for offshore wind resources near New England states are included in APPENDIX A.

Table 3-9. Gulf of Maine offshore wind technical resource potential by energy and capacity below [11] [22]

Water depth range (m)	Technical energy potential (GWh/yr)	Technical capacity potential (MW)
1-30	23,902	6,935
31-60	20,120	4,972
61-700	367,162	82,591
Total	411,184	94,498

Source: NREL

Figure 3-2. Map of Maine coastal ocean depths in relation to state water designation



Given the prohibition of offshore wind development in state waters, greater sea depths in federal waters, abundant offshore wind energy resource potential to serve Maine's electric needs, and projected reductions in floating wind costs (Section 3.2.4), this wind energy needs assessment assumes that 100% of the offshore wind serving Maine will be located in deep water and will leverage floating technology.

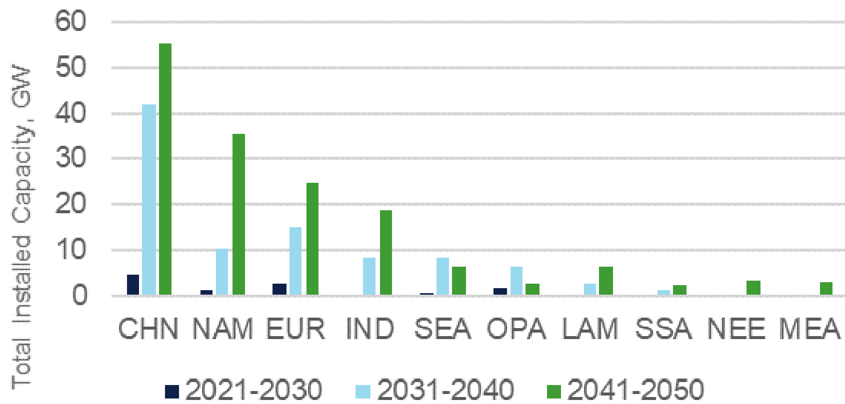
Assumption 2: 100% of offshore wind generation serving Maine in federal waters will be floating technology.

3.2.3 Development timelines

The Gulf of Maine is located close to New England population centers with high electrical demands, making it a good, long-term potential solution for supplying clean, renewable power in the region [21]. Despite its abundant potential wind resource, floating offshore wind is still nascent in its market maturity and is not expected to contribute significantly to Maine's 2030 RPS requirements.

DNV's 2021 Energy Transition Outlook (ETO) [17] forecasts the development of around 47 GW of floating offshore wind capacity in North America by 2050. Although the ETO does not go deeper than this continental perspective, this includes developments mostly off both the East and West Coasts. North America will see the globally second-most (after China) rapid floating wind capacity development in the decade 2040-2050 (see Figure 3-3 below).

Figure 3-3. Floating wind capacity growth by region by period (NAM = North America), DNV ETO

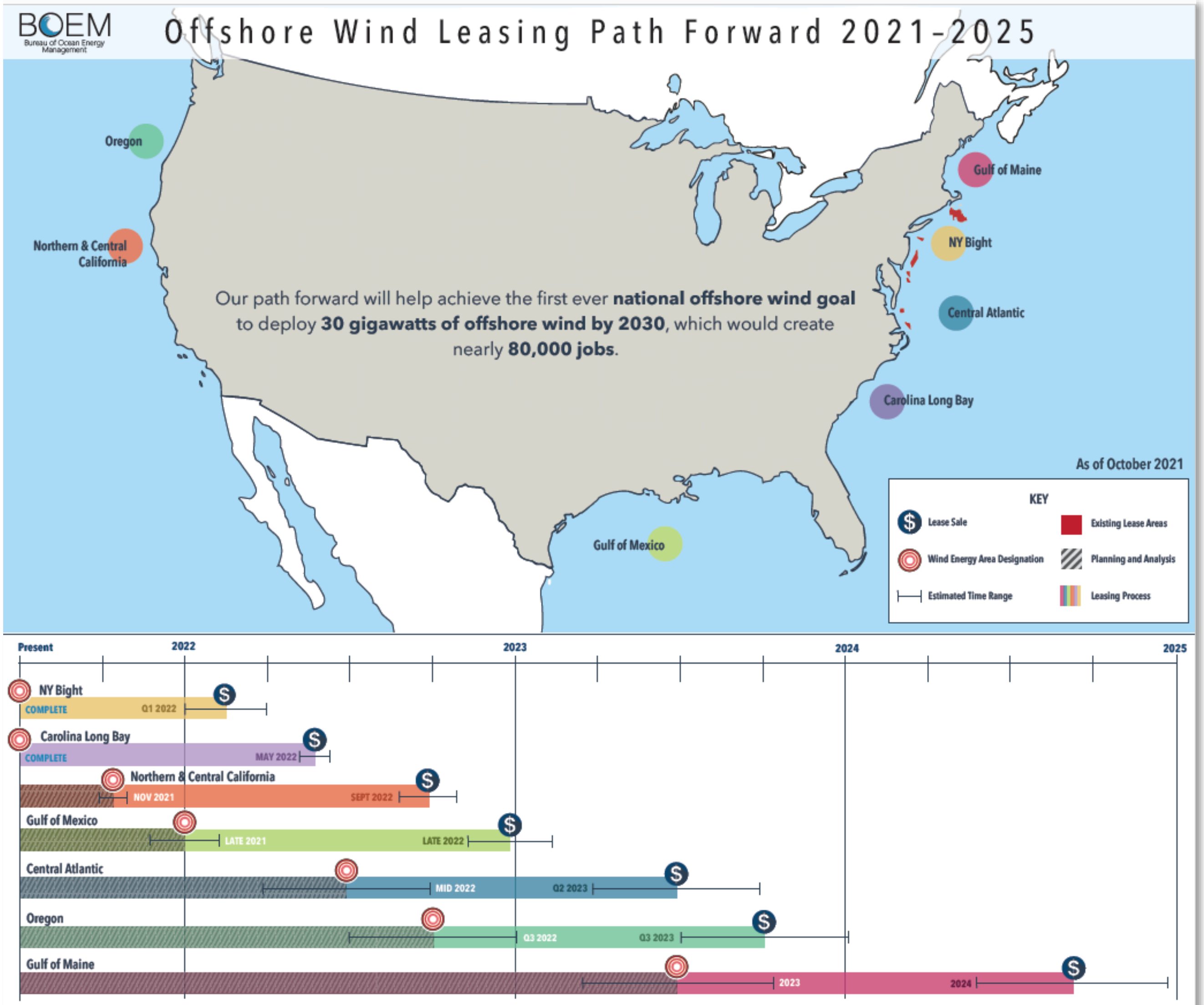


On the west and east coasts of the United States, the primary geographies where significant floating offshore wind development is expected are California, Oregon, and the Gulf of Maine. Three gigawatts of floating offshore wind by 2030 are currently under environmental and permitting review by BOEM and other authorities in Oregon [44]. An estimated 8.5 GW of floating offshore wind by 2045 is projected for three call-out[6] areas in California [45]. Massachusetts's *Energy Pathways for Deep Decarbonization* report modeled pathways for all of New England that included floating offshore wind capacity by 2050 ranging from 10.1 GW in an offshore wind constrained pathway to 26.8 GW in a limited efficiency pathway, with most floating offshore wind assumed to be built after 2030 [37]. At some point between 2035 and 2040, the dominant offshore wind technology installed in Massachusetts is expected to transition from fixed to floating offshore wind farms, after most of the potential sites for fixed offshore wind, including large areas not currently identified and available for lease, are built out [37].

The US federal government is taking steps to ramp up offshore wind resource development in federal waters. In March 2021, the US Secretary of the Department of the Interior outlined a plan for future offshore wind leasing by BOEM to meet the Biden-Harris administration's goal of deploying 30 GW of offshore wind energy by 2030 [14]. Later that year, the Biden Administration announced plans to hold up to seven new offshore lease sales by 2025, including in the Gulf of Maine (see Figure 3-4). BOEM plans to announce federal wind energy area designations and initiate the leasing process for the Gulf of Maine in mid-2023 and announce lease sales in mid-to-late 2024 [15].

[6] A call-out area is an area under consideration as a Wind Energy Area (WEA), which is an area open for auction bid solicitation.

Figure 3-4. BOEM offshore wind leasing path forward 2021–2025 [15]



Once leases are announced, the development, pre-construction, and construction of offshore wind farms are likely to take 7-10 years before commercial operation, depending upon many factors, most notably environmental and permitting factors [16]. Given the expected timeline for BOEM's announcement of lease sales in mid-to-late 2024 and typical offshore development timelines, it is expected that the earliest that this additional offshore wind could be operational is 2031.[7]

The project development lead times hereby presented account for the key project milestones listed below:

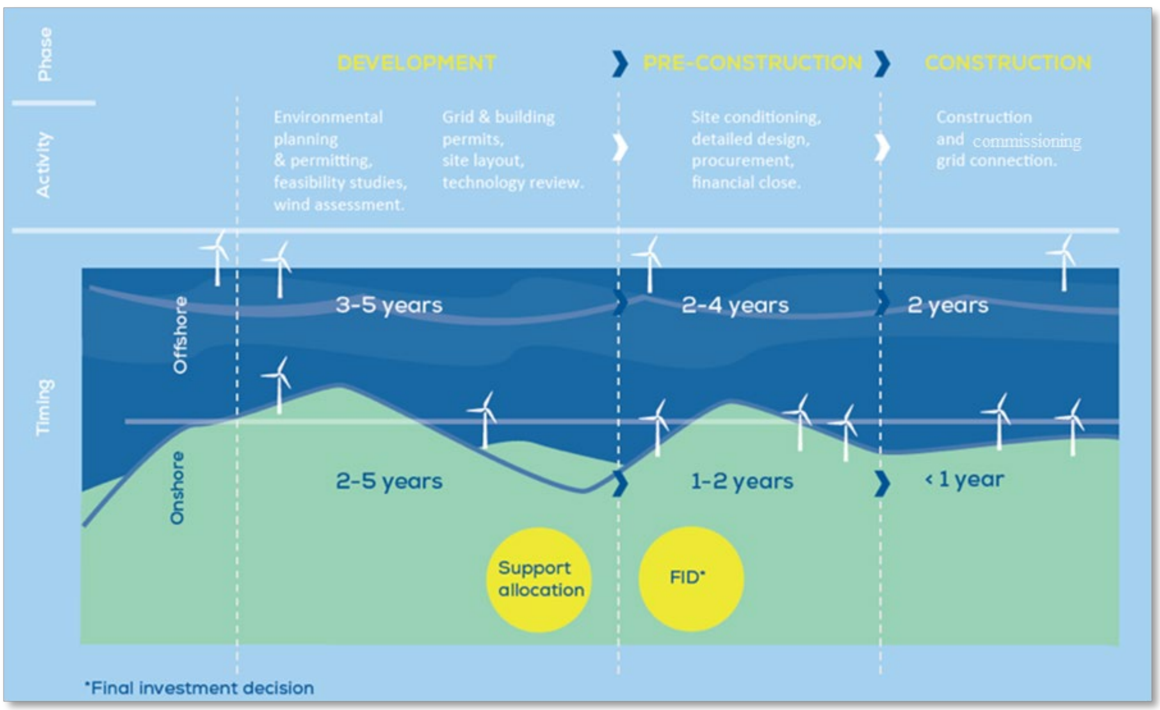
- Developer's site assessment plan (SAP) submission to BOEM
- Developer's construction and operations plan (COP) submissions to BOEM
- BOEM's review and approval of SAP and COP
- Detailed engineering and Certified Verification Agent (CVA)
- Fabrication and construction

[7] Beyond the 144 MW research array and 11 MW demonstration array

This development process requires a specific and stable regulatory environment, available seabed leases that facilitate such growth, port infrastructure, and a capable workforce and supply chain that can supply, fabricate, install, and operate the components of a floating wind farm. In addition, a sufficient and steady pipeline of projects will be necessary to justify the investment level associated with the necessary port upgrades to adapt the current infrastructure to the floating offshore wind logistic specificities. Limitations brought about by these factors will impact the real potential for floating offshore wind capacity development in the Gulf of Maine. Besides these supply chain, regulatory, and operational challenges, the actual floating capacity development also faces significant economic challenges. Finally, a state-of-the-art floating wind industry is significantly dependent on the development of solutions within a low technology readiness level (TRL) range. This means that the successes and failures of currently planned floating wind development (primarily in Europe) will drive the speed at which floating wind can be developed elsewhere, as it will affect technology acceptance, willingness to invest, and the understanding of whether design improvements are needed.

If any of these factors is lacking, it could contribute the delay of offshore wind farm deployment beyond the predicted 7-10-year timeline.

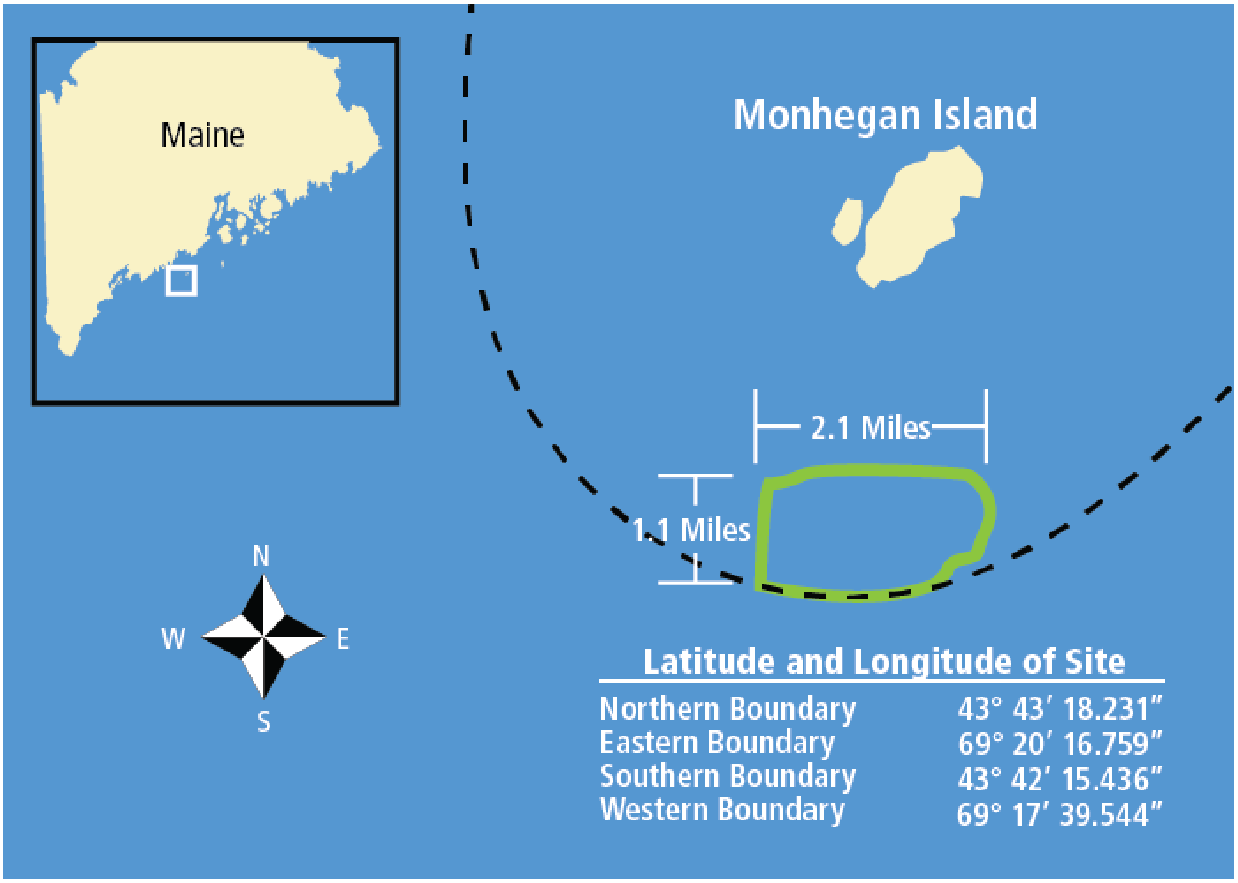
Figure 3-5. Typical offshore development timeline [16]



There are two offshore wind projects in the Gulf of Maine for which the development process has already begun: an 11 MW demonstration array near Monhegan island, and a 144 MW research array in federal waters. The development process for additional offshore wind in federal waters will begin soon but will be a long-term process.

The Aqua Ventus I demonstration array near Monhegan Island, consisting of an 11 MW turbine, is targeted for construction in 2024. The long-term project, initially begun in 2009, is being developed as a collaboration between the University of Maine, Diamond Offshore Wind, and RWE renewables. It is likely to be the first full-scale floating offshore wind turbine in the Americas [50].

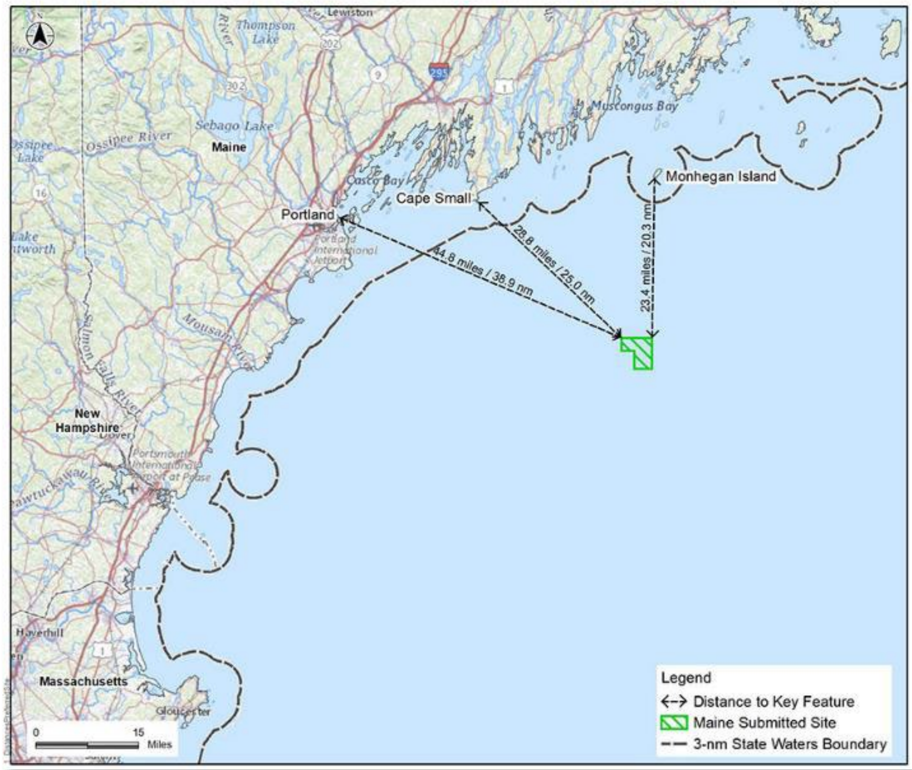
Figure 3-6. Aqua Ventus 1 floating offshore wind demonstration array [13]



In October 2021, the State of Maine applied to BOEM to lease a 15.2-square-mile area nearly 30 miles offshore in the Gulf of Maine for the nation's first floating offshore wind research site in federal waters (see Figure 3-7). The total capacity of this array is assumed to be 144 MW in 2026, although that date is uncertain given that the state is awaiting federal approval of the lease request. While there is no specific timeline required for BOEM to review the application submitted by the State of Maine, it is expected to be several years before all permitting is secured and construction can begin on this research array [13].

Assumption 3: The planned 144 MW research array and the 11 MW Aqua Ventus I demonstration project will be the only Gulf of Maine offshore wind projects completed by 2030.

Figure 3-7. Floating offshore wind research site [13]



3.2.4 Decreasing offshore wind levelized cost of energy

LCOE measures the cost of energy for producing one MWh of electricity over the lifetime of a power station. It measures the competitiveness of a power generation source and provides a resourceful metric to assess, rank, and quantify the feasibility of investing in different power station types.

LCOE estimates are in general sensitive to factors such as differences in site characteristics (e.g., wind speed and water depth), regulatory and market environment, calculation methods, assumptions about financing, and technology and market maturity. Hence, different LCOE estimates resultant from different models and different modeling assumptions will only be comparable to a certain extent.

Costs related to offshore wind development can be broken down into two main categories:

- Capital Expenditures (CAPEX), which are costs related to the constructional phase
- Operating Expenditures (OPEX), which are costs related to the operational phase

For offshore wind, the CAPEX can be divided further into turbine costs and other non-turbine investment costs such as those related to the foundation, installation, grid connection, and mooring if the turbine is floating. The capacity factor relates to the fraction of time that the turbine produces power at full capacity; a high-capacity factor will lead to high income and a reduced LCOE.

The cost trend projections for the LCOE for several different power station types are presented in Figure 3-8 are sourced from NREL [25] and DNV's 2021 Energy Transition Outlook [17].

Figure 3-8. Averaged LCOE by power station type [17] [25]

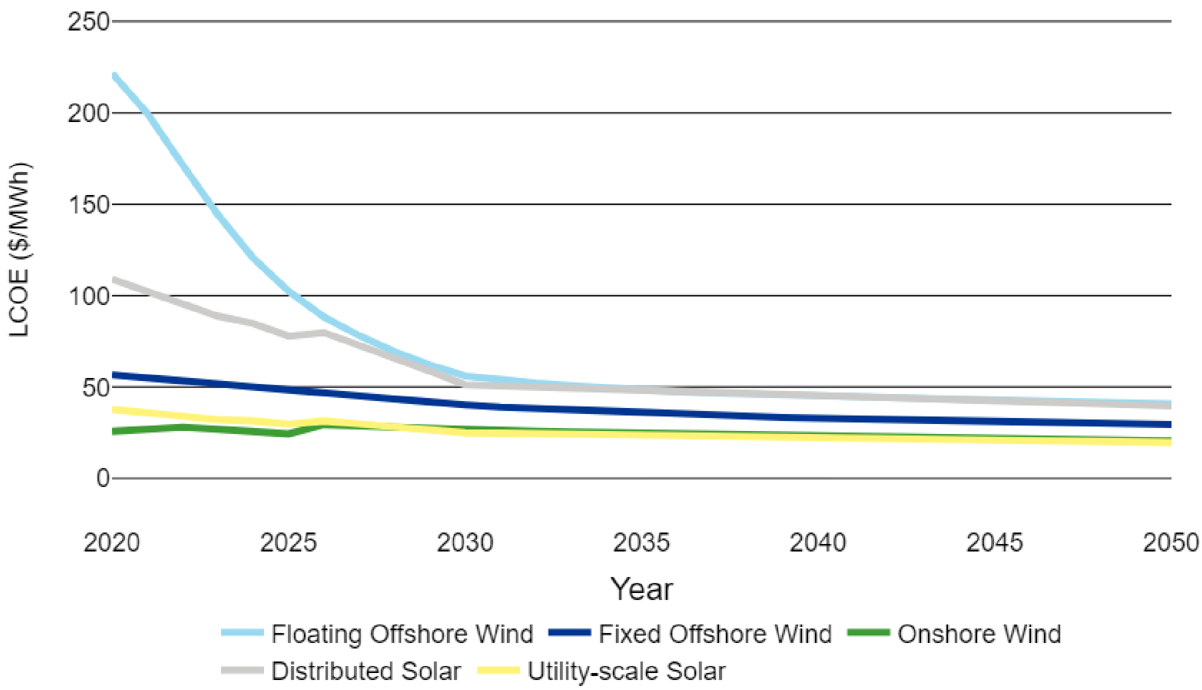


Table 3-10 shows projections of LCOE for onshore, fixed offshore, and floating offshore wind.

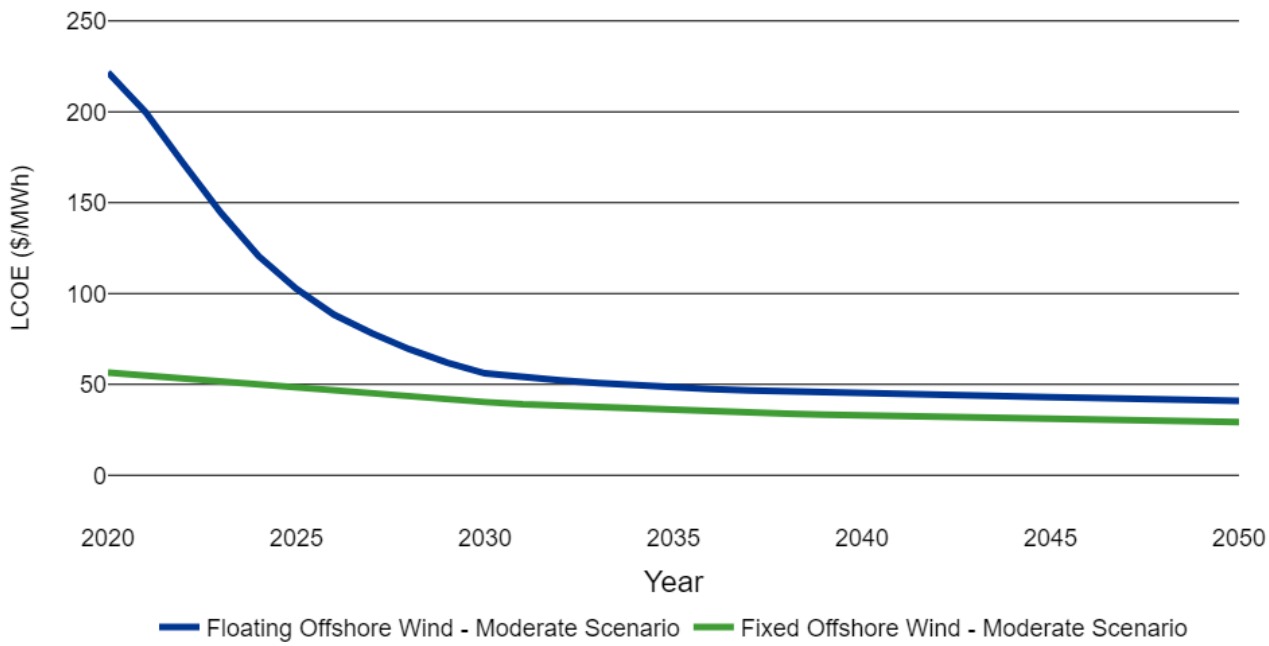
Table 3-10. Average North America LCOE for onshore, fixed, and floating offshore wind. Unit $/MWh [17] [25]

Year	Onshore wind[8]	Fixed Offshore Wind	Floating wind
2020	25	56	222
2050	20	29	40

Fixed offshore wind has achieved massive cost reductions during the last 10 years, sustained by the technology improvement, public funding aimed at increasing its cost efficiency, and incorporation of lessons learned from the first deployments in Northern Europe. In the US, NREL recently published a report indicating that the average LCOE of offshore wind farms commissioned from 2014 to 2019 has decreased by 40% [30]. Floating offshore wind is expected to follow a similar pattern, as the market is projected to mature over the next decade and leverage infrastructure upgrades in multiple geographies in addition to its remarkable industrialization potential. Projections for LCOE show a 48% reduction in fixed offshore wind LCOE from 2020 to 2050, compared to an 82% reduction in LCOE for floating offshore wind during the same period (Figure 3-9).

[8] Onshore wind LCOE was calculated leveraging the NREL Annual Technology Baseline electricity dataset [25],based on Maine specific wind speeds. This dataset does not differentiate between fixed-bottom and floating offshore wind costs, so costs from DNV's 2021 Energy Transition Outlook were used for both offshore wind types. These projections are based on DNV's global knowledge of the offshore wind industry evolution.

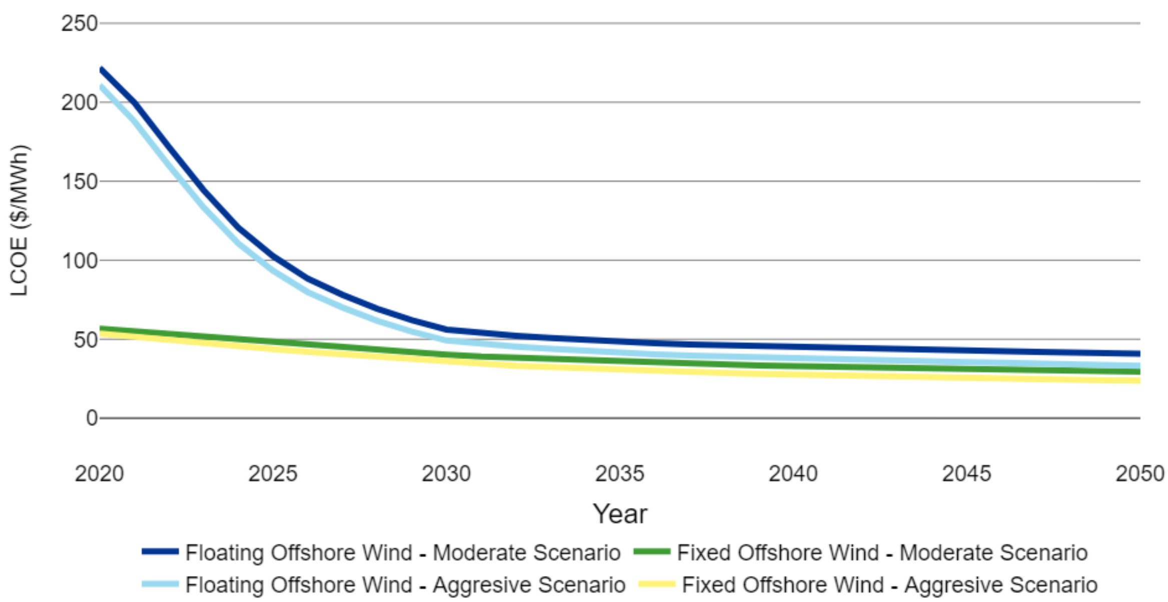
Figure 3-9. Predictions for Maine LCOE for floating and fixed offshore wind [17]



Many drivers are predicted to drive the drastic decrease in LCOE for floating wind in Maine, including the state's strong offshore wind resource, proximity to land-based electric grid and interconnections, proximity to on-shore assembly areas, availability of shore-based facilities and ports, and limited shallow and transitional water depths.

As LCOE is sensitive to the industrialization ability of each technology and scale of development, the LCOE model will be impacted by any limitations to large-scale developments. Figure 3-10 shows two possible scenarios for the reduction in fixed and floating offshore wind costs in time. The differences between the aggressive and moderate-cost-reduction scenarios represent uncertainties in how fast the technologies will scale, as well as other unavoidable uncertainties about future costs.

Figure 3-10. Moderate and aggressive LCOE scenarios for fixed and floating offshore wind [17] [25]



Assumption 4: Floating offshore wind will be cost-competitive with fixed offshore wind by 2050.

4 DATA SOURCE AND DETAILED PROCESS DESCRIPTION

DNV's analysis included evaluation and compilation of data in three primary areas to inform the model:

1. Total demand for renewable energy
2. Total expected renewable energy supply
3. Costs of Maine-based renewable energy resources and associated transmission

This section includes descriptions of the data used and the process employed to calculate each of these model inputs. As described in Section 3, the modeling process finds the annual net difference between projected demand for and expected supply of renewable energy, and then fills that renewable net short with the least-cost, Maine-based renewable resource. This process is conducted at the Maine-only level and at the total New England level. Table 4-2 below summarizes the primary data sources used in each step.

It is important to note that these descriptions include information about hourly data for both demand and supply of renewable energy. While these hourly data were used for exploratory analyses comparing supply and demand, only net annual supply and demand were used in the final calculation of the renewable net short and selection of renewable resources to fill the net short.

4.1 Demand

To determine renewable energy demand, DNV included total net demand projections by year through 2050 and load shapes, which show how demand is distributed over all 8,760 hours in a year. This was done for both Maine and New England region-level scenarios.

Different types of electricity load have different load shapes. For instance, the times of day when more people are charging their electric vehicles are different from the times of day when more people are using their heat pumps; usage patterns also differ from season to season. DNV separated demand projections into different load types. These types were traditional load, electrical vehicle load, residential heating and cooling load, and commercial heating and cooling load. DNV then multiplied the load-type-specific demand projections by normalized load shapes to generate hourly load projections for each load type to 2050. The load types were then added together to yield total hourly load projections.

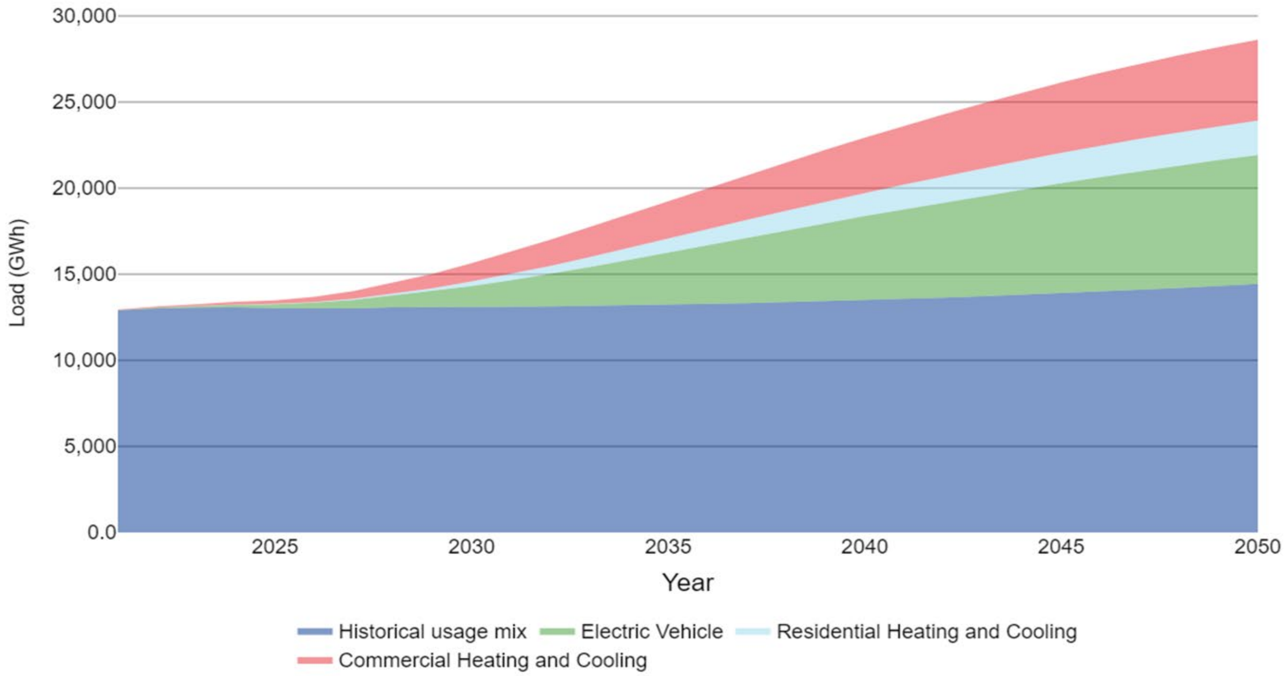
Finally, the total demand projections and projected load shapes were multiplied by the total fraction of electricity required to be renewable, based on each state's increasing RPS and the increase of these RPS percentages over time. This yielded the hourly projection of renewable demand to 2050, which was also aggregated to give yearly renewable demand projections.

4.1.1 Maine demand

4.1.1.1 Projected demand

For Maine electricity demand projections, DNV used data from greenhouse gas mitigation modeling performed by Synapse Energy Economics [47]. This work projected the amount of EV and heat pump adoption for Maine to meet its emissions reductions targets and the associated electricity load growth. This included different load projections by usage type, including historical usage mix, heating and cooling, and electric vehicle load. Figure 4-1 shows the Maine demand projections used in the scenario development.

Figure 4-1. Maine demand projections by demand type



DNV multiplied these demand projections by Maine's renewable portfolio standard percentages of 80% and 100% renewable by 2030 and 2050, respectively. We used a goal of 90% for 2040. This yielded the total renewable energy demand by year.

DNV compared these demand estimates to Massachusetts' 2020 *Energy Pathways to Deep Carbonization* report. In its highest demand scenario, the Massachusetts report estimates a demand of about 15 MWh per person-year in 2050, whereas the Synapse Energy Economics report for Maine estimates a demand of about 21 MWh per person-year. Given that both states have net-zero emissions goals by 2050, this large difference in energy demand is at first unexpected. However, the two states are very different, and Maine currently has approximately one-third more energy use per-person than Massachusetts. This could explain much of the difference. The projections from a variety of reports projecting demand (at the New England level) are explored more fully in Section 4.1.2.1.

4.1.1.2 Load shapes by demand type

To inform the model of scenario outcomes, DNV relied on the following data sources to calculate load shapes for the three demand types listed below:

- **Historical usage mix**: Maine's hourly load shape data was obtained from ISO-NE for the years 2003-2020 [32]. The average of these years was taken to obtain traditional load shape data for Maine.
- **Electric vehicle**: European EV load shape data was used to prepare transportation load shapes.
- **Residential and commercial heating**: DNV developed heating and cooling load shapes for residential and commercial customer types using load shapes originally developed for a Lawrence Berkeley National Laboratory (LBNL) project for ISO-New England (ISO-NE) in 2014 [33]. In that study, DNV developed weather-adjusted heating and cooling load shapes for all 9 regions of ISO-NE, and both commercial and residential sectors. The Maine-specific normalized heating and cooling load shapes from that work were used for this study.

4.1.2 New England demand

4.1.2.1 Projected demand scenarios to 2050 by demand type

For New England, DNV developed two scenarios to represent the spectrum of how fast electricity demand might increase in a decarbonizing region. The literature on this topic predicts a range of values, so we chose scenarios that would show both the low and high ends of this range.

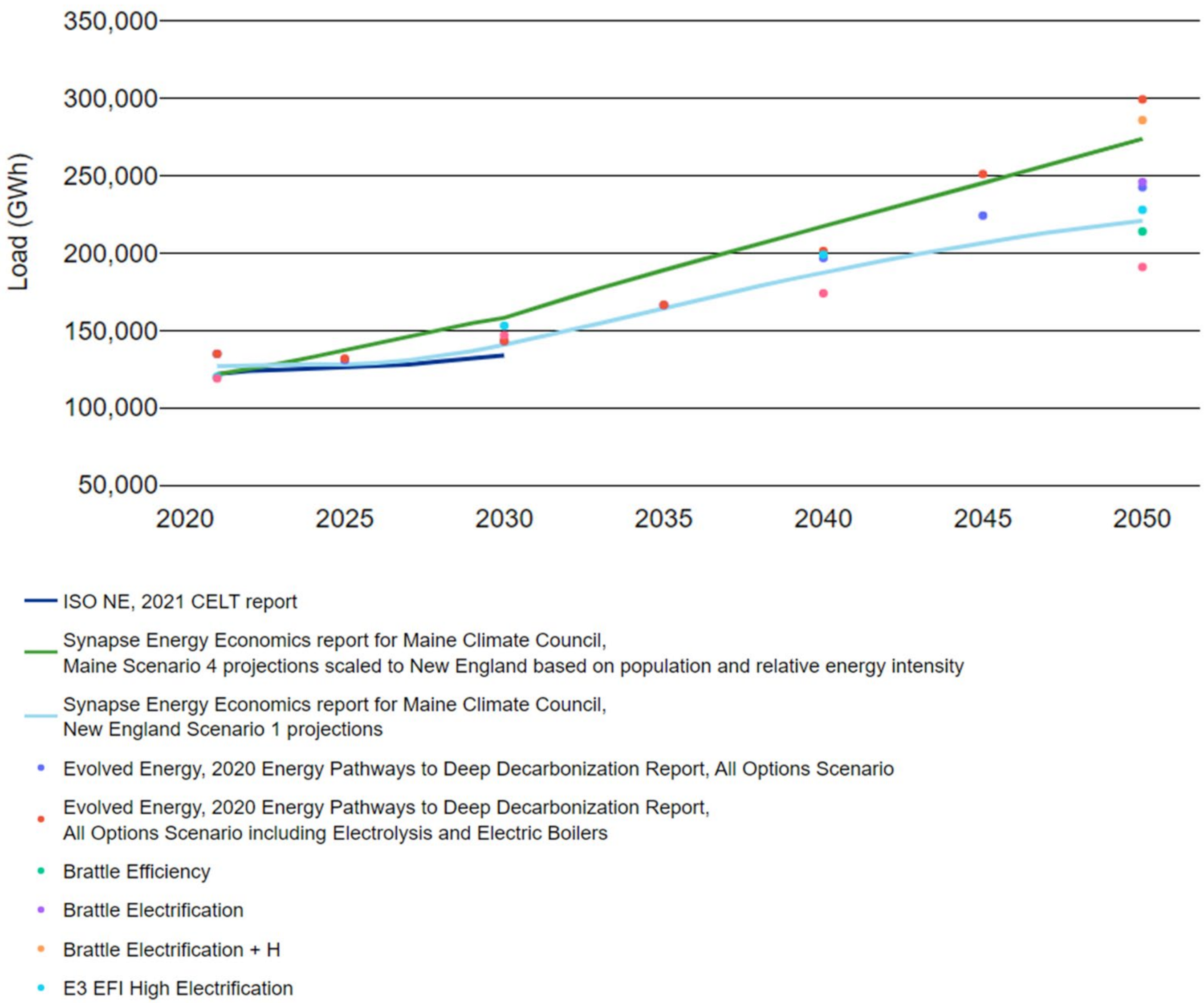
1. **Base case demand**. The lower-demand scenario was based on Synapse Energy Economics' Maine Climate Council report scenario T1/H1 [47]. In this scenario, Maine meets its goal of reducing emissions by 80% below 1990 levels by 2050. It assumes that other New England states have similar levels of electrification. This projection is in line with lower estimates from the range of values in the literature. It is important to note that, while this is the lower-demand scenario modeled, it is still an aggressive emissions-reduction scenario that involves large increases in electricity demand.
2. **Decarbonization demand.** The second method for projecting demand (the higher-demand-scenario) involved using Synapse's T4/H4 projected demand for Maine and scaling it up by state population and relative energy intensity to get projected demand for New England. For population numbers, DNV used projections published by the University of Virginia's demographics research group [35]. The research group published estimates for the years 2020, 2030, and 2040; the projected population from 2041 to 2050 was calculated using the average population growth rate of the previous decade. For energy intensity numbers, DNV used data from the US Energy Information Administration (EIA) for 2019 [48]. While there are differences in New England states' electricity-use mixes, this approach provides a reasonable estimate for electricity use in a high-electrification world.

Figure 4-2 shows the range of values in the literature and the projections chosen for our demand projection scenarios. We compared the base and decarbonization demand scenarios to projections from three recent reports. The first of these is Evolved Energy Research's *Energy Pathways to Deep Decarbonization* report, published in December 2020 to guide Massachusetts in achieving its goal of net zero greenhouse gas emissions by 2050 [37]. This report creates eight potential pathways for the state of Massachusetts and the New England region to achieve that goal, including electricity demand projections for each pathway. The second report we reviewed, *Net-Zero New England: Ensuring Electric Reliability in a Low-Carbon Future,* was written by Energy and Environmental Economics (E3) and the Energy Futures Initiative (EFI) in November 2020 and sponsored by Calpine Corporation [53]. This report examines how New England as a whole can reach net zero emissions by 2050 while maintaining electric reliability. Finally, we also include a comparison to projections reported by the Brattle Group in September 2019 for the Coalition for Community Solar Access that projected electric demand growth in the scenario in which New England reduced emissions by 80% by 2050 [52]. That presentation focuses on the whole New England region and explores three electricity demand growth projections.

The projections used in this report for the base demand scenario are shown in light blue, from Synapse Energy Economics New England Scenario 1 projections, are similar to ISO NE projections through 2030 (dark blue). By 2050, this base demand scenario falls above the E3/EFI High Fuels scenario but is similar to other low projections from the literature, including Brattle's efficiency scenario and the E3/EFI High Electrification scenario. The projections used for the decarbonization scenario are shown in green, and are from Synapse Energy Economics Maine Scenario 4, scaled up to New England by population and relative per capita energy intensity. This scenario is somewhat below the highest projections, from Evolved Energy's All Options scenario with electrolysis and electric boilers and Brattle's Electrification and Hydrogen scenario. It is, however, closer to these projections than the two mid-range options - Evolved Energy's baseline All Options scenario and Brattle's Electrification scenario (both of these without electrolysis and/or electric boilers, shown as red and mint green dots in Figure 4-2).

It is important to note that both the scenarios used in this work imply large amounts of electrification across energy use sectors. The difference between them represents the uncertainty in the pace and magnitude of electrification that states will be able to achieve, as well as uncertainty around emerging technologies like hydrogen and electric boiler adoption.

Figure 4-2. Demand projections for the New England region from various studies [47][51][52][53]



4.1.2.2 Load shapes by demand type

To inform load shapes by demand type, DNV relied upon the following data sources and processes for the three demand types below:

- **Traditional**: New England's hourly load shape data was obtained from the ISO-NE for the years 2003-2020 [55]. The average of these years was taken to obtain traditional load shape data for New England.
- **Electric vehicle**: European EV load shapes data was used to prepare transportation load shapes.
- **Residential and commercial heating**: DNV developed heating and cooling load shapes for residential and commercial customer types using load shapes originally developed for an LBNL project for ISO-New England (ISO-NE) in 2014 [33]. In that study, DNV developed weather-adjusted heating and cooling load shapes for all 9 regions of ISO-NE and both commercial and residential sectors. Weighting the heating and cooling load shapes was done by applying the corresponding degree days for New England.

The figures below depict the demand projections used to develop the New England scenarios. Figure 4-3. shows the New England demand projections under the decarbonization scenario and Figure 4-4. shows the base case demand.

Figure 4-3. Decarbonization demand scenario: New England demand projections by type

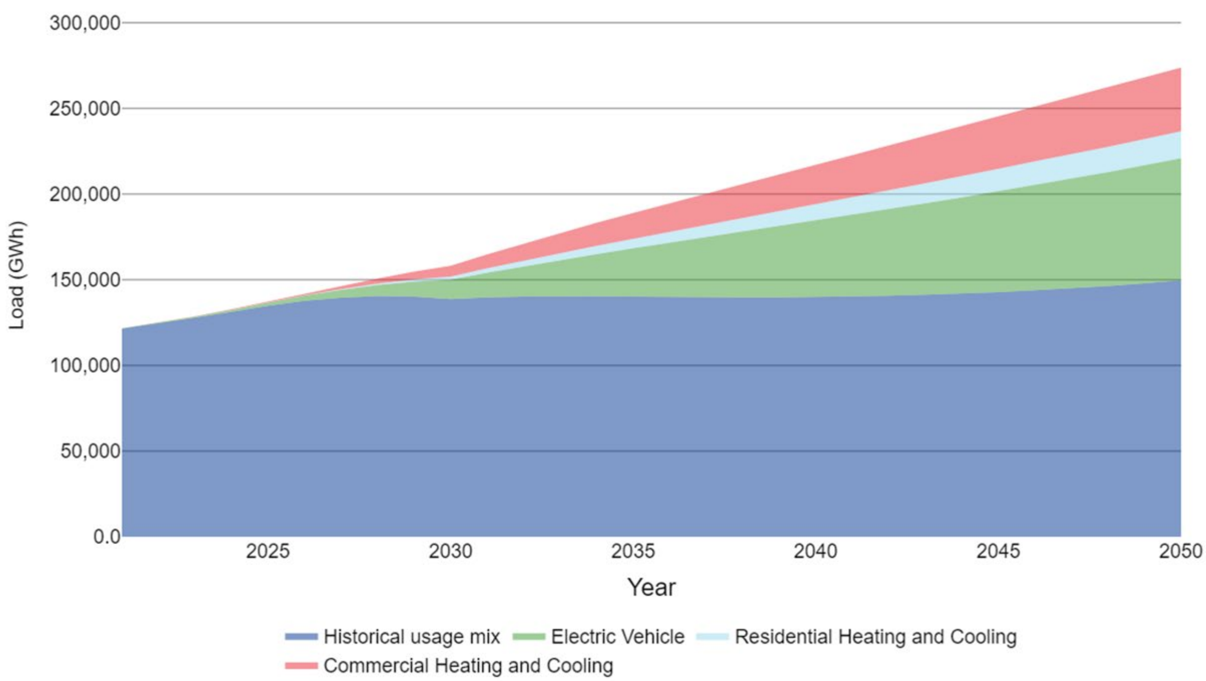
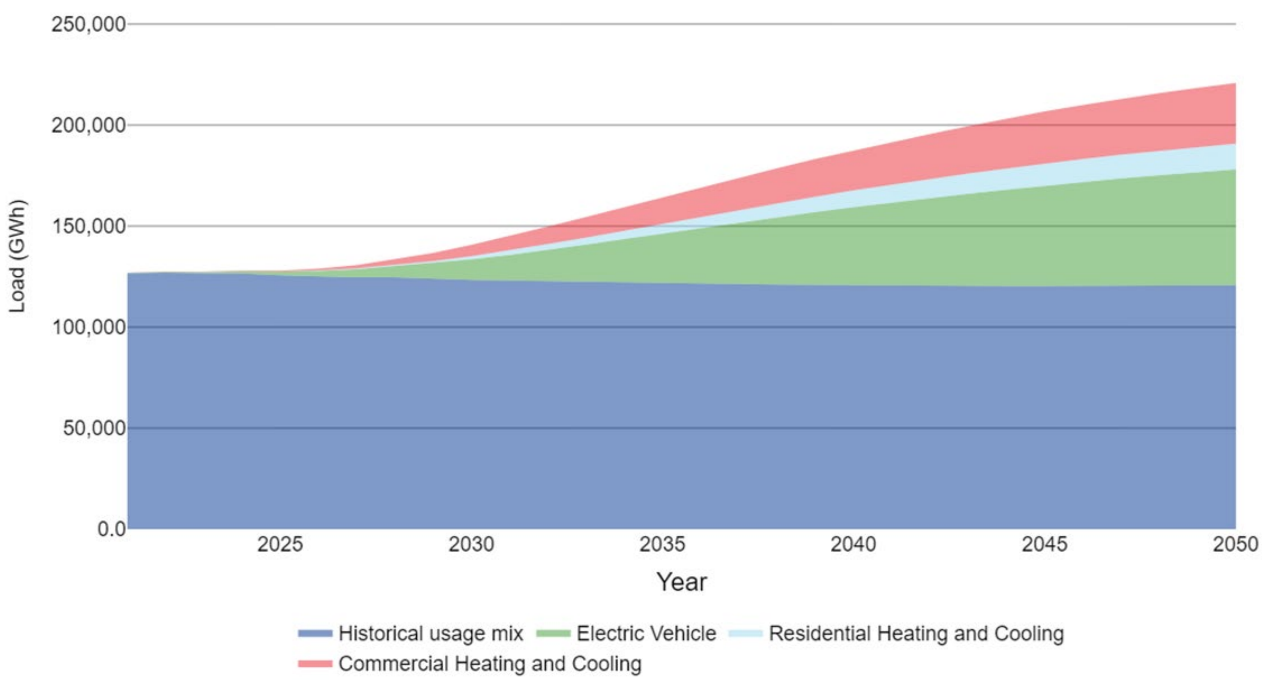


Figure 4-4. Base case demand scenario: New England demand projections by type



4.1.2.3 Renewable demand projections by demand type

The renewable energy fractions assumed for New England were those in the State of Maine REGMA [2], with corrections to two New England state RPS goals. The original REGMA numbers are shown on the left, below, in Figure 4-6. The updated RPS numbers are shown on the right, in Figure 4-5. Because most states did not have an RPS goal for 2040, a halfway goal between 2030 and 2050 was assumed.[9]

[9] Most New England states have similar and/or complementary policies in place to support their decarbonization efforts, such as clean energy standards

Figure 4-6. REGMA: New England States RPS in 2050

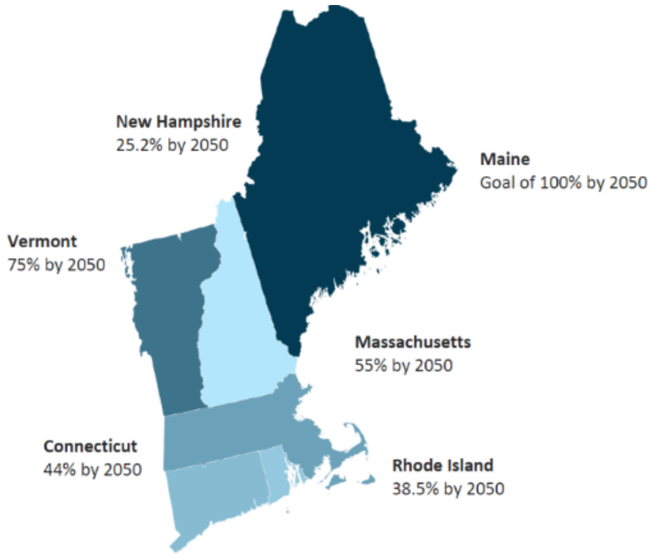
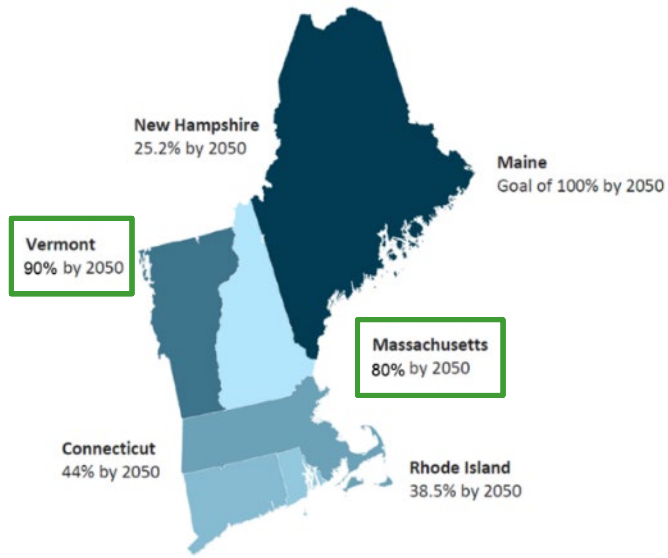


Figure 4-5. Updated: New England States RPS in 2050



The projected renewable demand is calculated by multiplying the state-population-weighted RPS by the New England demand projections, for each year.[10] This was done for each of the two New England demand projection scenarios.

4.2 Supply

After determining total renewable demand by year, at the Maine and New England levels, DNV assessed the supply available and needed to meet that demand.

- For Maine, we subtracted the currently existing renewable energy supply from demand to estimate the need for additional renewables. The remainder is referred to as the renewable net short, and we chose the least-cost remaining available renewable resource in Maine to fill that net short until the full need was fulfilled every year.
- For New England, projections of renewable resource capacities to 2050 were created. For onshore renewables, the draft 2050 ISO-NE Grid and Transmission Planning study was used for these projections (a source based on Evolved Energy's 2020 report) [51]. Projections of offshore wind capacities were based on commitments by states that have made them, shown in Section 4.2.1. The net short in New England was calculated by subtracting total existing and projected renewable resource generation from total renewable need. To determine the extent to which Maine resources could help fill that regional need, we again, chose the least-cost remaining available renewable resource in Maine, until the net short was fulfilled every year.

Existing and projected supply at the hourly level was also calculated, as an exploratory analysis (though the supply needed to fill the remaining hourly need was not). To do this, first, the amount of each renewable resource in a given year was identified, along with the average generation shape (the hourly amount of energy per installed MW) that the resource was likely to produce. Then, the installed capacity was multiplied by the generation shape to determine the likely amount of renewable energy produced by the relevant resource for every hour of the year. Finally, those generation shapes were summed over all renewable resources. To get annual numbers, those shapes were aggregated up to give the annual MWh supplied.

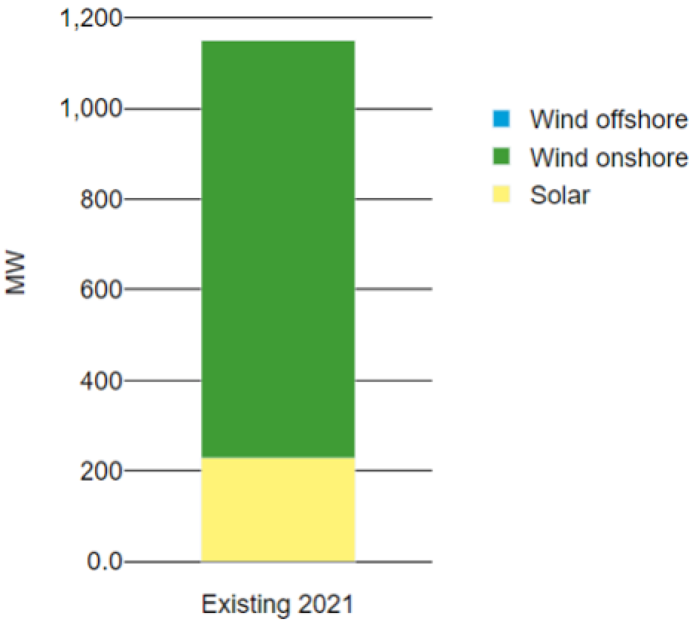
[10] In June 2022, after completion of this analysis, Rhode Island approved legislation requiring that 100% of the state's electricity be offset by renewables by 2033.

4.2.1 Current and planned renewable mix

4.2.1.1 Maine

For Maine, DNV reviewed EIA data [34] and the State of Maine REGMA [2] to produce a full picture of the installed capacity of each renewable energy resource. Current onshore wind, hydroelectric, natural gas, and biomass capacity was sourced from EIA's State Electricity Profile [28]. The Maine Governor's Energy Office website specifies 2021 solar and storage capacity [7]. These solar capacities were combined with EIA data to get a split between utility-scale solar PV and distributed solar. Figure 4-7 shows the existing renewable resources in Maine in 2021; these values were used as assumptions in the scenario modeling.

Figure 4-7. Estimated existing renewable resources in Maine in 2021



Imports and exports. For the purpose of this analysis, DNV assumed that imports to both Maine and New England will remain at similar levels in the future (i.e., no increases in imports beyond the NECEC). Total imports to New England and Maine were calculated based on the 2021 *Net Energy and Peak Load by Source* report from ISO-NE. Interconnections with New Brunswick (NB Power), Hydro Quebec, and the New York Northern AC tie were used to quantify flows between Maine and external sources [55].

The proportion of renewable resources in the generation mixes for NB Power, Hydro Quebec, and New York Northern AC, are generation assets or generation listed in, respectively, the NB Power 2020 Integrated Resource Plan, the Hydro Quebec 2020 annual report [57], and the EIA net electric generation by source state summary for October 2021 [58]. We assumed that all net imports via New Brunswick interconnection are used to supply energy demand in Maine and the remaining imports necessary to support load in Maine are sourced evenly from Hydro Quebec and New York Northern AC.

Renewable energy credits. We also considered whether to include renewable energy credits (RECs) as a source to serve existing and/or future renewable energy requirements. Every year, the RECs from a fraction of renewable generation in Maine are sold through the New England Power Pool (NEPOOL) to fulfill other states' RPS targets, and Maine suppliers purchase some RECs from generators in other New England states. The flow of RECs in and out of Maine depends on the different states' annual RPS targets, the number of RECs generated in each state, how many RECs from each state qualify for the different states' different tiers of RPS targets (i.e., different classes of RECs), and the alternative compliance payment

(ACP) set by each state. For Maine to ensure that in any one year it can meet its RPS targets, the simplest goal (and most effective in combating climate change) will be to help ensure that enough RECs are generated for all of New England to meet RPS targets.

Given the complexity of REC trading into the future and its dependence on state policy, we did not include the flow of RECs in our renewable energy accounting for Maine needs. Instead, we focus on having sufficient renewable energy generation in Maine and the Gulf of Maine to serve the state's electricity demand on an annual basis.

4.2.1.2 New England

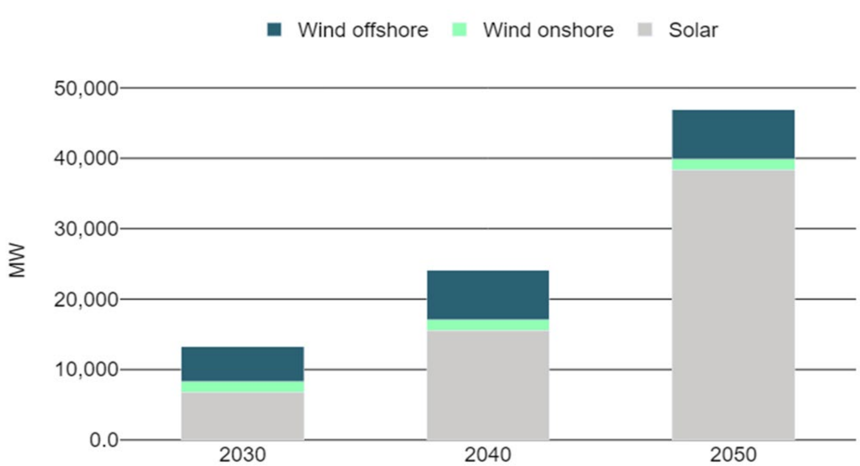
To determine projected New England generation, DNV combined renewable projections from the draft 2050 ISO-NE Grid and Transmission Planning study [59] (based on Evolved Energy's 2020 study [51]) with current capacity amounts from EIA [34] to determine projected New England generation. These were added to projections of offshore wind capacities, which were based on commitments by states that have made them, shown below in Table 4-1.

Table 4-1. Offshore wind targets (model assumes procurements through 2050) (MW)

State	REGMA Assumptions [2]	Updated Assumptions
Maine	-	-
New Hampshire	-	-
Vermont	-	-
Massachusetts	3,200 by 2035	4,000 by 2027 [40]
Connecticut	2,000 by 2030	
Rhode Island	-	1,000 by 2030 [41]

Figure 4-8 integrates the ISO-NE projections with the offshore wind projections, showing the New England resource assumptions used in the scenario modeling.

Figure 4-8. Estimated existing and planned renewable resources in New England through 2050



4.2.2 Renewable generation shapes

While DNV did not assess the amount of renewable resources needed to meet hourly demand, we conducted an exploratory analysis to compare supply and demand on an hourly basis. To get the hourly generation shapes for that analysis, we modeled current and projected renewable generation sites, both in Maine and New England. This allowed us to create renewable generation shapes for all the generation types in the model. Maine shapes were an average of Maine generation sites and shapes for the rest of New England were an average of non-Maine generation sites. These shapes were normalized such that they represented the hourly generation per MW of installed capacity and could easily be scaled up to any level of installed resource capacity. Again, these hourly amounts were not used in resource selection, but are shown in APPENDIX C.

4.2.3 Maine resource selection

After determining the amount of current (for Maine) or current and projected (for New England) renewable resources, DNV selected the lowest-cost Maine-based renewable resource to fill the net short each year. The assumptions about the availability of those resources are described in Section 3.1.4. The data and methods used to estimate the cost of each resource, which included both generation and transmission costs, are described below.

4.2.3.1 Renewable generation LCOE

DNV used the following two methods to estimate renewable generation costs for Maine. First, DNV developed cost estimates for Maine using data published by the National Renewable Energy Laboratory (NREL) [62]. Costs are calculated using the following LCOE equation:

*LCOE = (FCR * CAPEX + FOM/ CF * 8760 hours/year) + VOM + FUEL*

Abbreviation	Definition
LCOE	Levelized cost of energy
FCR	Fixed charge rate
CAPEX	Capital expenditures
CRF	Capital recovery factor
FOM	Fixed operation and maintenance expenses
VOM	Variable operation and maintenance

To simplify the calculation, the following assumptions were made:

- Cost recovery period and the technical life of the technology were assumed to be 30 years.
- Onshore wind speed class was determined using wind speed figures published by the Office of Energy Efficiency and Renewable Energy.
- The “Market + Policies” financial assumption was selected from NREL’s LCOE calculation tool. As described by NREL, this assumption “allows technology-specific changes to debt interest rates, return on equity rates, and debt fraction to reflect effects of R&D on technological risk perception” and also adds in variation due to long-term trends “as well as effects of tax reform and tax credits” [62].

The *2021 Energy Transition Outlook* (ETO) report was published by DNV [17]. The fifth edition of DNV's widely referenced ETO presents the results of DNV’s independent model of the world’s energy system, covering the period through to 2050, and forecasts the energy mix, supply, and demand globally and in 10 world regions. The ETO suite of reports covers issues like the scaling of key technologies, changes in climate policy, and the financing of the energy transition. The ETO's power economics section published cost estimates for North America for floating and fixed offshore wind which were used as LCOE estimated for the moderate scenario. These LCOE estimates for fixed and floating offshore wind were used alongside NREL's advanced technology innovation scenario to generate fixed and floating LCOE for an advanced scenario [19].

4.2.3.2 Transmission cost estimates

The transmission cost estimates in this report are derived from those used in the State of Maine REGMA [2], the ISO NE 2016/2017 Maine Resource Integration Study [61], and the ISO NE Final Second Maine Resource Integration Study [46]. In these sources, new transmission is approximated to cost between $0.6 and $1.2 million per MW of new resource construction. We assumed that the first half of the onshore wind and solar resources available would cost approximately the lower of these two prices, and the second half would cost approximately the higher price. We also added an element of random variation to the first half of the resource available, to simulate the difference in cost faced by projects with different distances for interconnection. For distributed solar, we assumed that the first 750 MW would be built under Maine's Net Energy Billing (NEB) program. We assumed that distributed solar above that 750 MW would face higher transmission costs of about $1.3 million per MW, based on assumptions from the REGMA.

For offshore wind transmission costs, DNV assumed that transmission would cost $10 million per mile of undersea cable, substations would cost $40 million each, and that lines would connect to existing infrastructure near population centers, so no additional onshore transmission would be needed. We also assumed that each transmission line and transformer station would serve about 1,400 MW. The first 5 GW of offshore wind is assumed to be, on average, 30 miles from shore. The remaining 15 GW of offshore wind is assumed to average 60 miles from shore. This would result in transmission costs of about $0.28 million per MW and $0.73 million per MW for the first 5 and remaining 15 GW of offshore wind, respectively. These assumptions do not represent exact knowledge of costs or what infrastructure will be required, but are best estimates based on DNV's global and regional industry experience with recent offshore wind projects.

4.3 Data summary

A summary of the primary model inputs, sources, and usage is provided in Table 4-2.

Table 4-2. Data sources by data type and model use

Data Type	Region	Period	Source	Use in Model
Demand	Maine	2021-2050	Synapse Energy Economics report	Total electricity demand
Demand	New England, Base scenario	2021-2050	Synapse Energy Economics report, New England Scenario 1	Total electricity demand
Demand	New England, Decarbonization scenario	2021-2050	Synapse Energy Economics report, extrapolated Maine demand, Scenario 4	Total electricity demand
Renewable electricity demand	Maine and New England	2030-2040	State RPS standards in statute; ME REGMA report	Multiplied by total electricity demand to get renewable demand
Renewable supply	Maine	2021	EIA	Subtracted from renewable demand to get renewable net short

Data Type	Region	Period	Source	Use in Model
Renewable supply	Maine	2022-2050	--	Output
Renewable supply	New England outside Maine	2021	EIA	Subtracted from renewable demand to get renewable net short
Renewable supply	New England outside Maine	2022-2050	ISO NE 2050 transmission study	Subtracted from renewable demand to get renewable net short
ME renewable generation potential	Maine	--	REGMA, DNV experts	Model can choose up to these amounts of renewable generation
LCOE of ME renewables	Maine	2021-2050	NREL, DNV	Model selects least-cost (energy and transmission) resources first
Transmission costs of ME renewables	Maine	2021-2050	ISO-NE (onshore), DNV (offshore wind)	Model selects least-cost (energy and transmission) resources first

A summary of the data sources referenced are provided in Table 4-3 below.

Table 4-3 Data sources reference list

Data	Source
Maine climate goals	Maine Climate Council. December 2020. Maine Won't Wait. https://www.maine.gov/future/sites/maine.gov.future/files/inline-files/MaineWontWait_December2020.pdf
State RPSs and offshore wind targets (except for states listed below which were updated from this report)	State of Maine Governor's Energy Office. March 2021. State of Maine Renewable Energy Goals Market Assessment. https://www.maine.gov/energy/sites/maine.gov.energy/files/inline-files/GEO_State%20of%20Maine%20Renewable%20Energy%20Goals%20Market%20Assessment_Final_March%202021_1.pdf
MA offshore wind target	An Act Creating a Next-Generation Roadmap for Massachusetts Climate Policy. Section 1 of Chapter 21N. Bill S.9. (2021).
RI offshore wind target	Office of Energy Resources. October 27, 2020. Press releases: Raimondo calls for up to 600 MW of new offshore wind energy for Rhode Island. https://www.ri.gov/press/view/39674
MA RPS	State of Massachusetts. Program Summaries. https://www.mass.gov/service-details/program-summaries
VT RPS	State of Vermont, Department of Public Service. Renewables. https://publicservice.vermont.gov/renewable_energy#:~:text=The%202016%20Vermont%20Comprehensive%20Energy%20Plan%20%28CEP%29%20sets,energy%20in%20our%20electric%2C%20transportation%2C%20and%20heating%20sectors

Data	Source
Key underlying assumption	An Act To Prohibit Offshore Wind Power Development in Territorial Waters and Submerged Lands of the State. Chapter 407. S.P. 512 - LD 1619. (2021). http://www.mainelegislature.org/legis/bills/getPDF.asp?paper=SP0512&item=5&snum=130
Key underlying assumption	An Act To Require Prompt and Effective Use of the Renewable Energy Resources of Northern Maine. Chapter 380. S.P. 563 - LD 1710. (2021). https://legislature.maine.gov/LawMakerWeb/summary.asp?paper=SP0563
Forecast of capacity, energy, loads, and transmission	ISO New England. April 30, 2021. CELT Reports. 2021 CELT Report 2021-2030 Forecast Report of Capacity, Energy, Loads and Transmission. https://www.iso-ne.com/system-planning/system-plans-studies/celt
Existing Maine generation data	US Energy Information Administration. August 19, 2021. Maine. https://www.eia.gov/state/analysis.php?sid=ME
Maine procurement pipeline data	S&P Capital IQ dataset of projects
Wind speed figures for Maine's Coast	US Department of Energy, Office Energy Efficiency and Renewable Energy (EERE) Gulf of Maine Offshore Wind Speed at 100 Meters. https://windexchange.energy.gov/maps-data/337
LCOE for renewable projects	National Renewable Energy Laboratory. Annual Technology Baseline, Equations and Variables in the ATB. https://atb.nrel.gov/electricity/2021/equations_&_variables
Offshore wind cost scenarios	National Renewable Energy Laboratory. October 8, 2020. Data Show Big Gains for Offshore Wind. https://www.nrel.gov/news/program/2020/2019-offshore-wind-data.html
Offshore wind LCOE	US Department of Energy, Office of Renewable Energy and Energy Efficiency. August 30, 2021. *Offshore Wind Market Report: 2021 Edition*. https://www.energy.gov/sites/default/files/2021-08/Offshore%20Wind%20Market%20Report%202021%20Edition_Final.pdf
Offshore wind LCOE. Floating offshore wind capacity forecast.	DNV. 2021. Energy Transition Outlook. https://eto.dnv.com/2021
Maine load shapes data (2003-2020)	ISO-New England. Energy, Load, and Demand Reports. https://www.iso-ne.com/isoexpress/web/reports/load-and-demand/-/tree/zone-info
EV load shapes	DNV European Electricity Market simulation model.
Residential and Commercial heating and cooling load shapes	Lawrence Berkeley National Laboratory. 2014. End-Use Data Development for Power System Load Model in New England – Methodology and Results. https://eta.lbl.gov/publications/end-use-data-development-power-system

Data	Source
Sector load data	US Energy Information Administration. October 7, 2021. Annual Electric Power Industry Report, Form EIA-861 detailed data files. https://www.eia.gov/electricity/data/eia861/
Population projections	University of Virginia. December 2018. National population projections. Prepared by: Weldon Cooper Center, Demographics Research Group. https://demographics.coopercenter.org/national-population-projections/
Global floating offshore wind capacity forecast	DNV. 2021. Pathway to Net Zero. https://eto.dnv.com/2021/about-pathway-to-net-zero
Comparable floating offshore wind capacity forecast	HM Government. November 2020. The Ten Point Plan for a Green Industrial Revolution. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf
National floating offshore wind capacity forecast	Musial, W., P. Beiter, D. Heimiller, and G. Scott. 2016a. 2016 Offshore Wind Energy Resource Assessment for the United States (Technical Report). NREL/TP-5000-66599. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy16osti/66599.pdf
Comparable floating offshore wind market	State of Oregon. Floating Offshore Wind Study: Benefits & Challenges for Oregon. https://www.oregon.gov/energy/energy-oregon/Pages/fosw.aspx
Comparable floating offshore wind market	Rose, A.; Wei, D.; Einbinder, A. August 2021. California's Offshore Wind Electricity Opportunity. http://schwarzeneggerinstitute.com/images/files/OSW_Report.pdf
Neighboring floating offshore wind capacity forecast	Commonwealth of Massachusetts. Energy Pathways to Deep Decarbonization. Prepared by: Evolved Energy Research. https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report/download
State floating offshore wind capacity forecast	University of Maine. Advanced Structures & Composites Center. https://composites.umaine.edu/offshorewind/
State floating offshore wind capacity forecast	Musial, W. February 2017. Offshore Wind Resource, Cost, and Economic Potential in the State of Maine. NREL/TP-5000-70907. National Renewable Energy Laboratory (NREL), Golden, CO (US). https://www.nrel.gov/docs/fy18osti/70907.pdf
Maine transmission costs	ISO-New England. October 30, 2020. Final Second Maine Resource Integration Study. https://www.iso-ne.com/static-assets/documents/2021/01/second-maine-resource-integration-study-report-non-ceii-final.pdf
Demand projections	State of Maine. August 7, 2020. Volume 3: Mitigation Modeling Consolidated Energy Sectors Modeling Results. Prepared by: Hall, J.; Knight, P.; Frost, J.; Letendre, S. (Synapse Energy Economics)

5 RESULTS

This section presents the results for each of the scenarios modeled (scenarios 1-6 in Table 5-1) along with brief insights into key findings arising from the analysis. Though distributed and utility-scale solar resources were modeled separately, in the below tables they are combined for simplicity. The projections of capacity needs are included here, while projections of energy needs (GWh by resource) are included in APPENDIX D. APPENDIX E provides a combined view of the resource capacity and energy generation profiles of all scenarios described here.

For clarity, this analysis focuses on **resources located in Maine or the Gulf of Maine** and how those resources can serve either Maine or New England. These results include **only new resources** in Maine, beyond those that already exist. The modeling approach incorporates assumptions regarding additional renewable energy development in other states; however, the following charts are intended to illustrate expected builds in Maine only.

Table 5-1. Matrix of demand and supply scenarios

		Supply		
		COD	UOD	DP
New England Demand	Base Case Demand	1	3	5
	Decarbonization Demand	2	4	6

5.1 Scenario 1 – Base Case Demand / Constrained Onshore Development

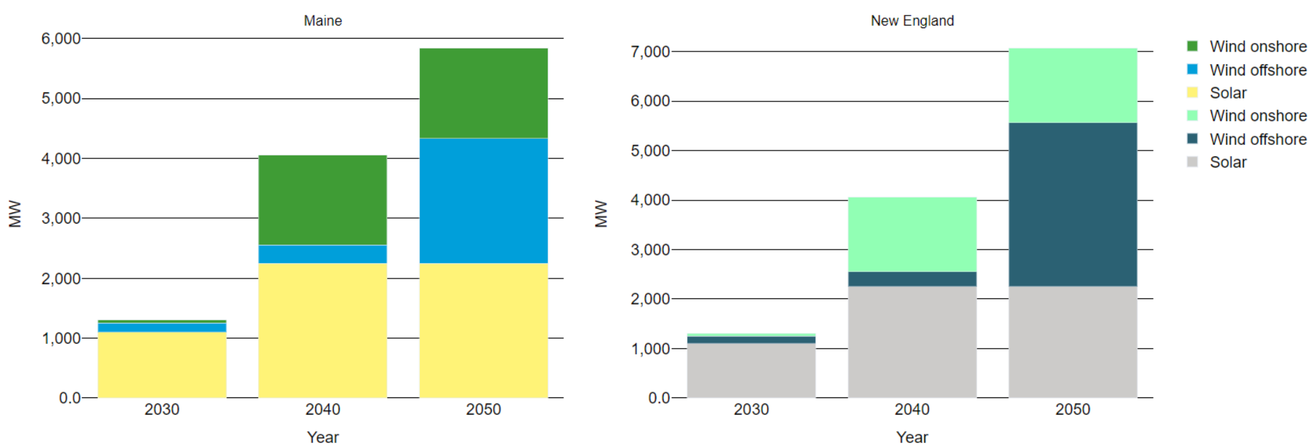
Scenario description: This scenario assumes the base demand projection for New England combined with no additional onshore transmission developed (and no additional land needed for this development) in Maine beyond LD 1710 and other existing pipeline projects (1,993 MW).

Key findings: Given the limitations on onshore development, Gulf of Maine floating offshore wind will be developed to serve both Maine and the broader New England region. This scenario projects 2,776 MW by 2050 for Maine and a total of 4,002 MW for New England, which would serve all remaining renewable energy needs. This scenario would require an estimated 170 to 234 additional miles of onshore transmission lines, with associated land use.

Table 5-2. Scenario 1 projections of additional Maine capacity (MW) to serve Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,100	1,917	1,917	1,100	1,917	1,917
Onshore wind	51	826	826	51	826	826
Offshore wind	155	995	2,776	155	995	4,002

Figure 5-1. Scenario 1 projections of additional Maine capacity (MW) to serve Maine and New England demand



5.2 Scenario 2 –Decarbonization Demand / Constrained Onshore Development

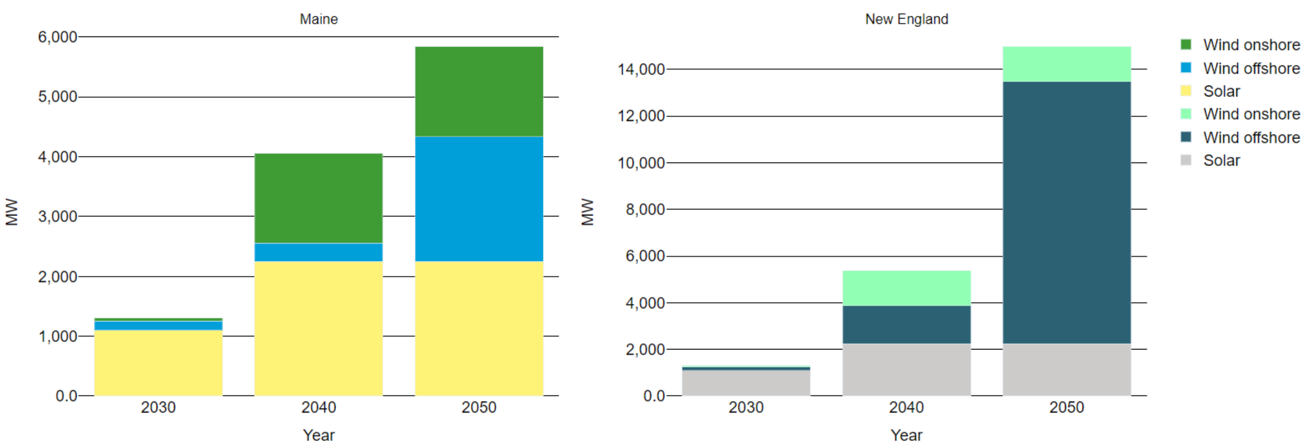
Scenario description: This scenario assumes the decarbonization demand projection for New England combined with no additional onshore transmission developed (and no additional land needed for this development) in Maine beyond LD 1710 and other existing pipeline projects (1,993 MW). Minimal onshore resources are developed and offshore wind development proceeds quickly and extensively.

Key findings: Given the limitations on onshore development, Gulf of Maine floating offshore wind is developed to help Maine meet its renewable energy needs (2,776 MW by 2050), with additional offshore capacity (11,906 MW total) to serve New England. This scenario would require an estimated 170 to 234 additional miles of onshore transmission lines, with associated land use.

Table 5-3. Scenario 2 projections of additional Maine capacity (MW) to serve Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,100	1,917	1,917	1,100	1,917	1,917
Onshore wind	51	826	826	51	826	826
Offshore wind	155	995	2,776	155	2,310	11,906

Figure 5-2. Scenario 2 projections of additional Maine capacity (MW) to serve Maine and New England demand



5.3 Scenario 3 – Base Case Demand / Unconstrained Onshore Development

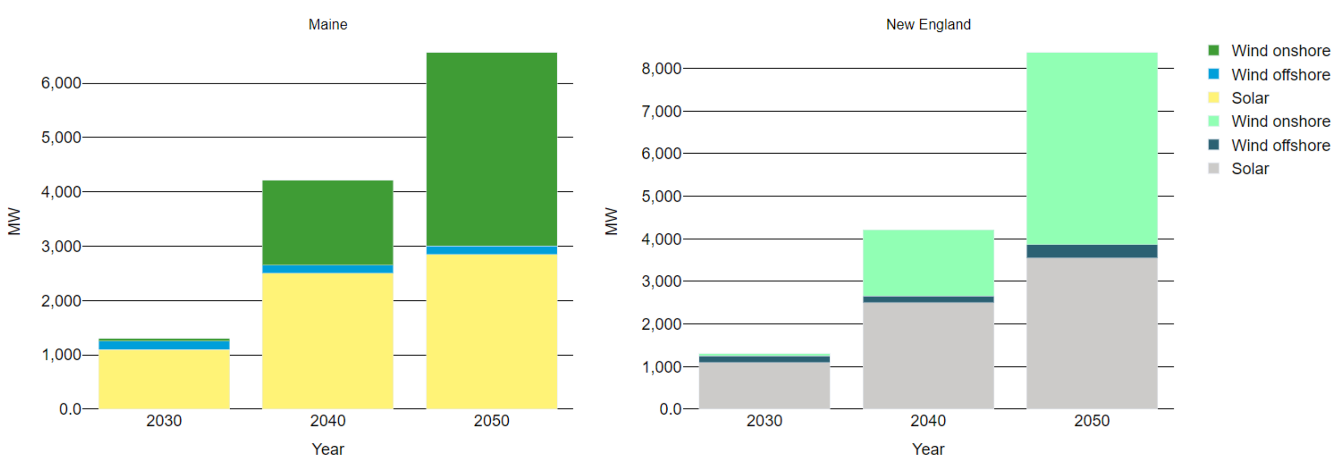
Scenario description: This scenario assumes the base demand projection for New England combined with aggressive projected reductions in offshore wind costs. Land use in Maine for additional onshore solar and wind development and associated transmission is unlimited.

Key findings: Despite aggressive offshore wind cost projections, onshore wind, solar PV, and significant new associated transmission infrastructure are constructed to serve the majority of the energy needs of Maine, while a diverse mix of lower-cost resources, including some floating offshore in the Gulf of Maine, ramp up by 2050 to serve the broader New England region renewable energy needs. This scenario would require an estimated 1,202 to 2,835 additional miles of onshore transmission lines, with associated land use.

Table 5-4. Scenario 3 projections of additional Maine capacity (MW) to serve Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,100	2,500	2,850	1,100	2,500	3,550
Onshore wind	51	1,556	3,555	51	1,556	4,500
Offshore wind	155	155	155	155	155	317

Figure 5-3. Scenario 3 projections of additional Maine capacity (MW) to serve Maine and New England demand



5.4 Scenario 4 –Decarbonization Demand / Unconstrained Onshore Development

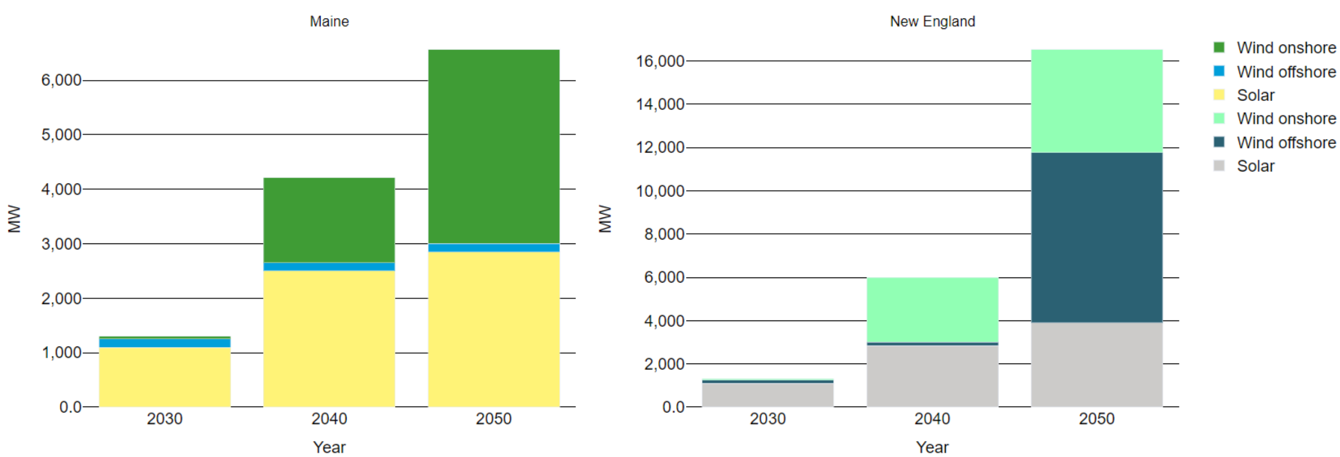
Scenario description: This scenario assumes the decarbonization demand projection for New England combined with aggressive projected reductions in offshore wind costs. Land use in Maine for additional onshore solar and wind development and associated transmission is unlimited.

Key findings: Even with the lowest projected offshore wind costs, onshore wind and solar PV are still lower-cost resources. Maine meets its needs through onshore wind development, solar PV, and the research array and Monhegan projects. Offshore wind is available to be developed in the Gulf of Maine to serve New England's renewable energy needs between 2040 and 2050 (7,871 MW). This scenario would require an estimated 1,202 to 2,835 additional miles of onshore transmission lines, with associated land use.

Table 5-5. Scenario 4 projections of additional Maine capacity (MW) to serve Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,100	2,500	2,850	1,100	2,850	3,900
Onshore wind	51	1,556	3,555	51	2,985	4,750
Offshore wind	155	155	155	155	155	7,871

Figure 5-4. Scenario 4 projections of additional Maine capacity (MW) to serve Maine and New England demand



5.5 Scenario 5 – Base Case Demand / Diverse Portfolio

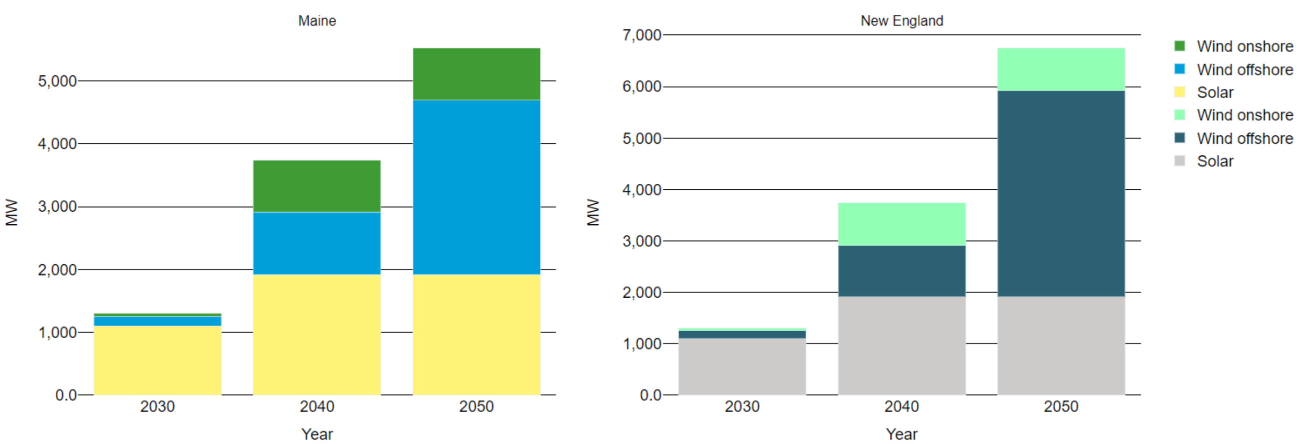
Scenario description: This scenario assumes the base demand projection for New England and incorporates elements of both the Constrained onshore development and Unconstrained onshore development scenarios. It assumes the same aggressive cost reductions for offshore wind and assumes the development of moderate additional on-shore transmission to enable a total of 3,000 MW of additional on-shore wind and/or solar generation located in Maine.

Key findings: Moderate amounts of solar PV, onshore wind and offshore wind provide Maine with a diverse mix of renewable energy capacity while all renewable energy needs are met to achieve the State's 100% renewable energy goal. For New England, offshore wind development in the Gulf of Maine gradually ramps up starting around 2040 with more than 3,312 MW installed by 2050. This scenario would require an estimated 449 to 614 additional miles of onshore transmission lines, with associated land use.

Table 5-6. Scenario 5 projections of additional Maine capacity (MW) to serve Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,100	2,250	2,250	1,100	2,250	2,250
Onshore wind	51	1,500	1,500	51	1,500	1,500
Offshore wind	155	305	2,086	155	305	3,312

Figure 5-5. Scenario 5 projections of additional Maine capacity (MW) to serve Maine and New England demand



5.6 Scenario 6 – Decarbonization Demand / Diverse Portfolio

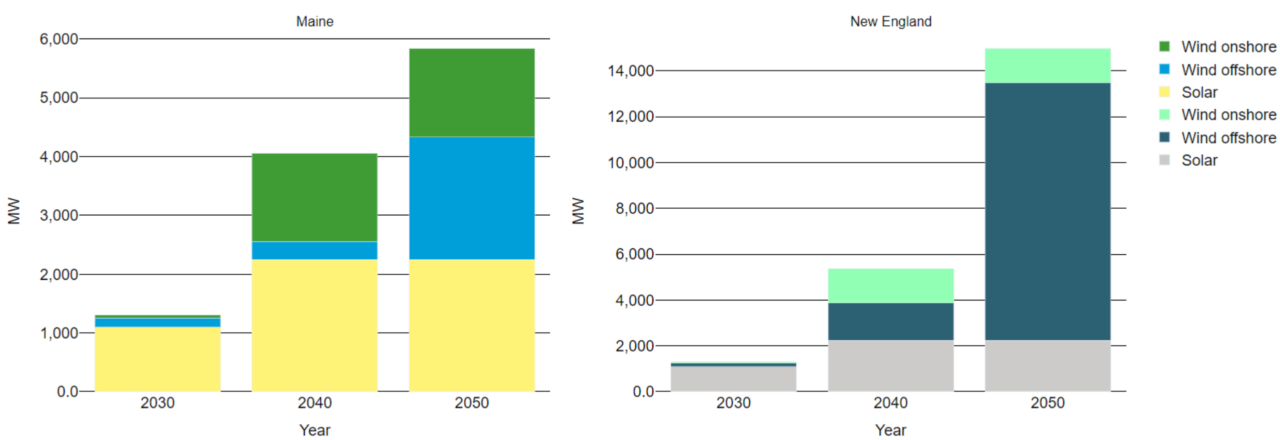
Scenario description: This scenario assumes the decarbonization demand projection for New England and incorporates elements of both the Constrained onshore development and Unconstrained onshore development scenarios. It assumes the same aggressive cost reductions for offshore wind and assumes the development of moderate additional on-shore transmission to enable a total of 3,000 MW of additional on-shore wind and/or solar generation located in Maine.

Key findings: Maine, like in Scenario 5, leverages a diverse portfolio of renewable energy to attain its 100% renewable energy goals, while 11,216 MW of offshore wind serves the needs of a highly electrified New England region. This scenario would require an estimated 449 to 614 additional miles of onshore transmission lines, with associated land use.

Table 5-7. Scenario 6 projections of additional Maine capacity (MW) by resource, to serve Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,100	2,250	2,250	1,100	2,250	2,250
Onshore wind	51	1,500	1,500	51	1,500	1,500
Offshore wind	155	305	2,086	155	1,619	11,216

Figure 5-6. Scenario 6 projections of additional Maine capacity (MW) to serve Maine and New England demand



5.7 Combined scenario data

The following sections aggregated the results for each of the scenarios by year and then in conjunction with the renewable input assumptions for both Maine and New England.

5.7.1 Combined resource capacity scenarios

Combining the individual results above helps compare the resources projections across supply and demand scenarios, and over time.

Figure 5-7 presents the Maine projections and Figure 5-8 and Figure 5-9 present the New England projections.

Figure 5-7. Maine resource projections for each demand scenario

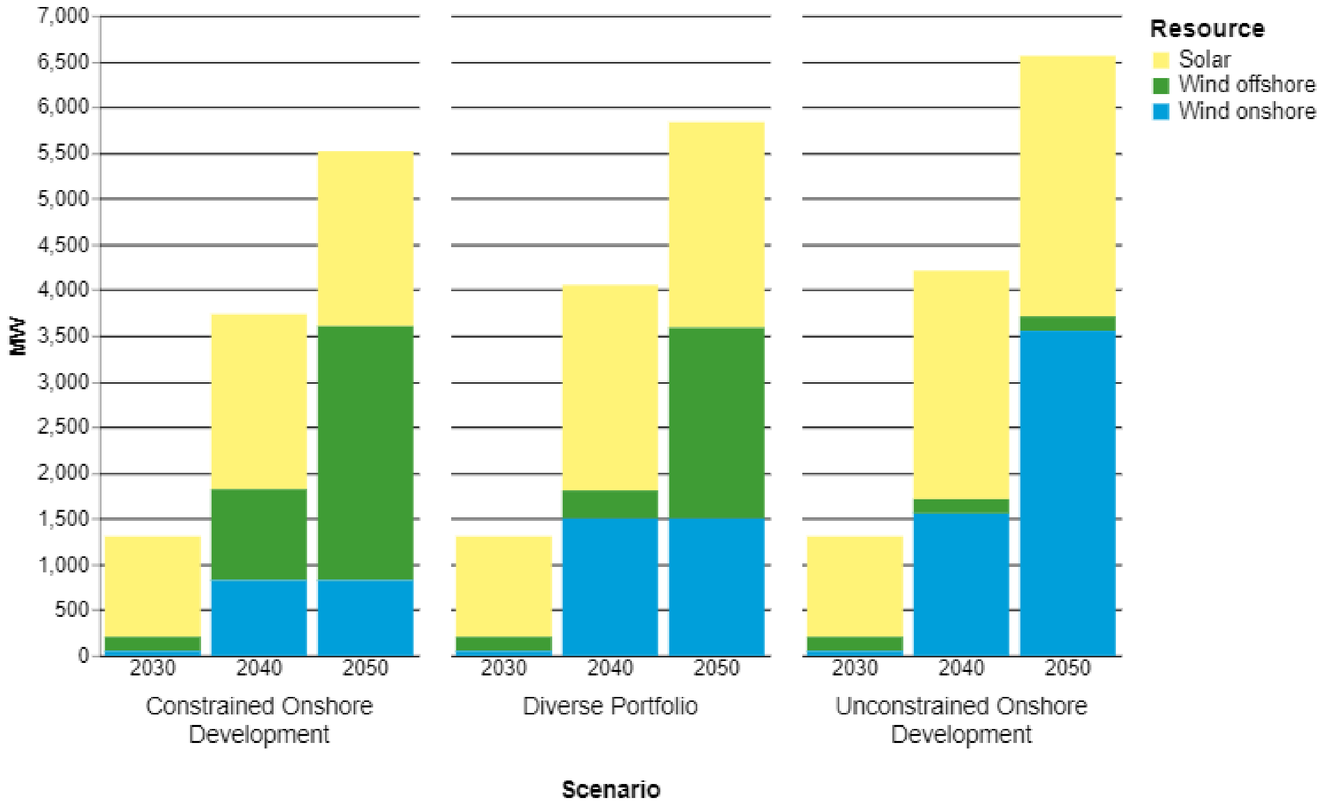


Figure 5-8. New England resource projections for base demand

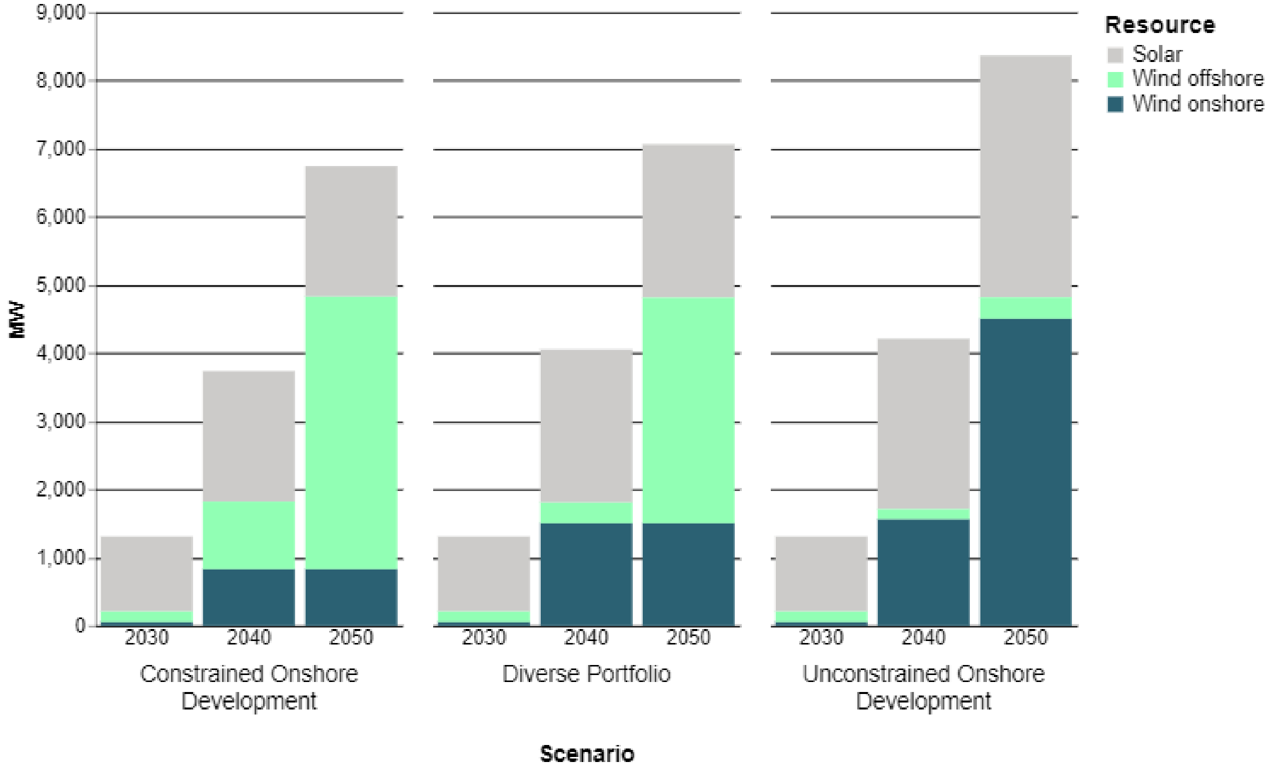
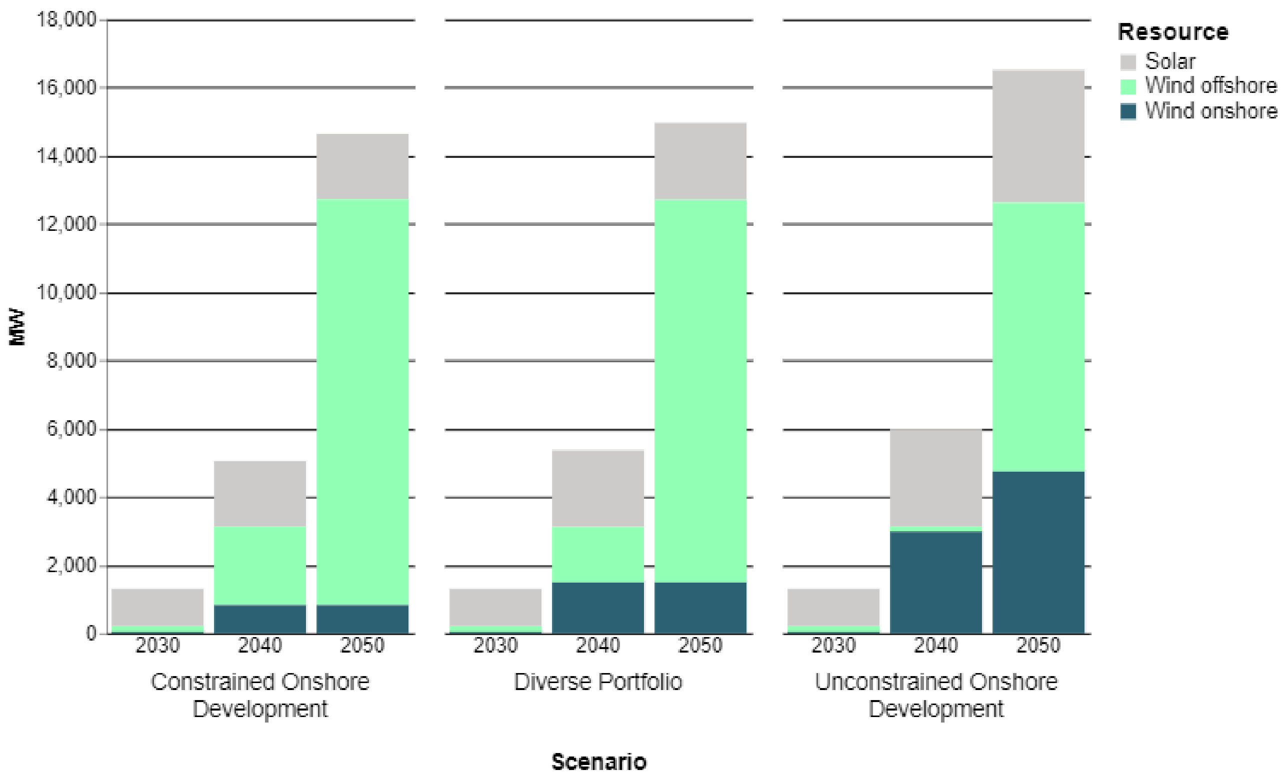


Figure 5-9. New England resource projections for decarbonization demand



5.7.2 Total projected renewable supply

The figures below integrate the scenario outputs presented in Sections 5.1 through 0 with the renewable supply assumptions introduced in Section 4.2.1 to show the total projected renewable supply to meet each of the demand scenarios.

Figure 5-10. Maine total resource projections for supply scenarios

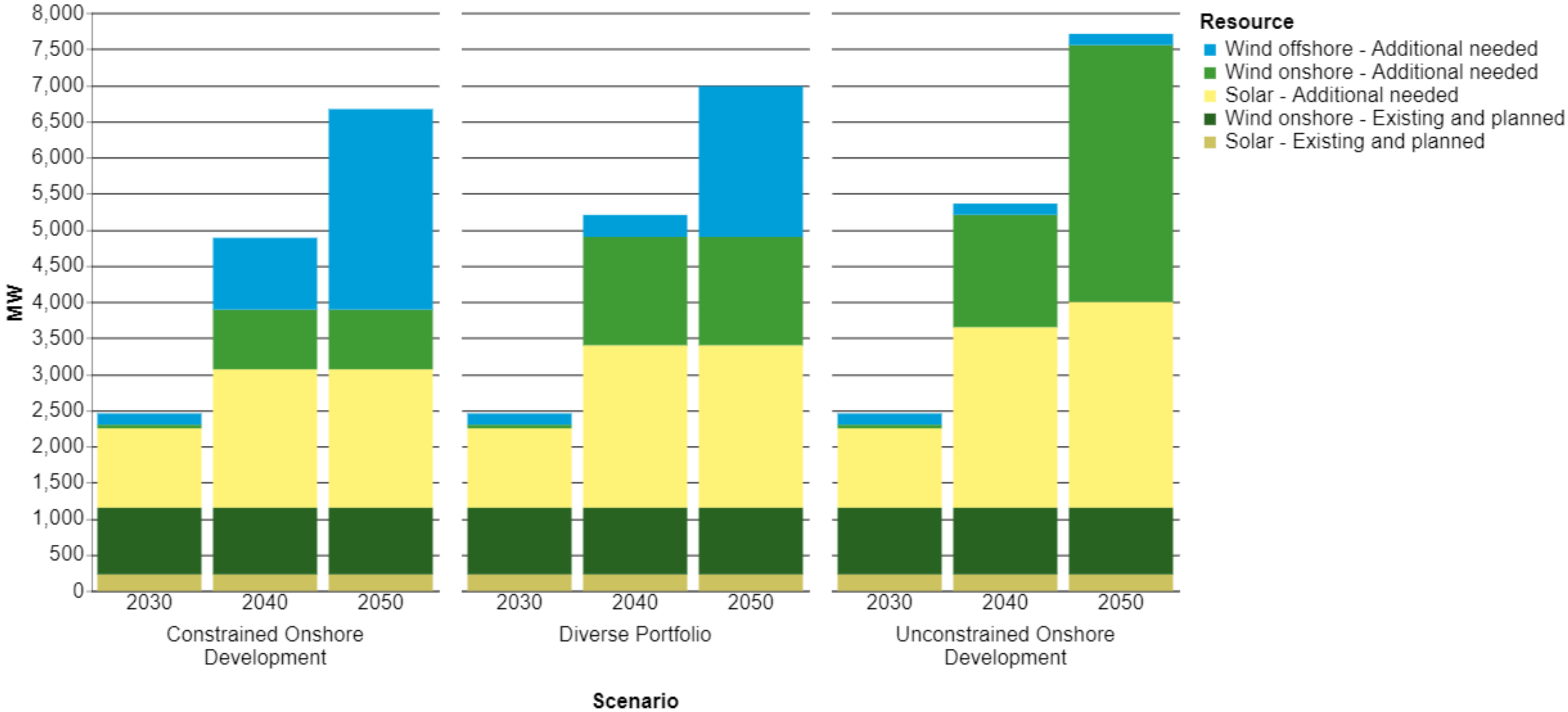


Figure 5-11. New England total resource projections for supply scenarios, base demand

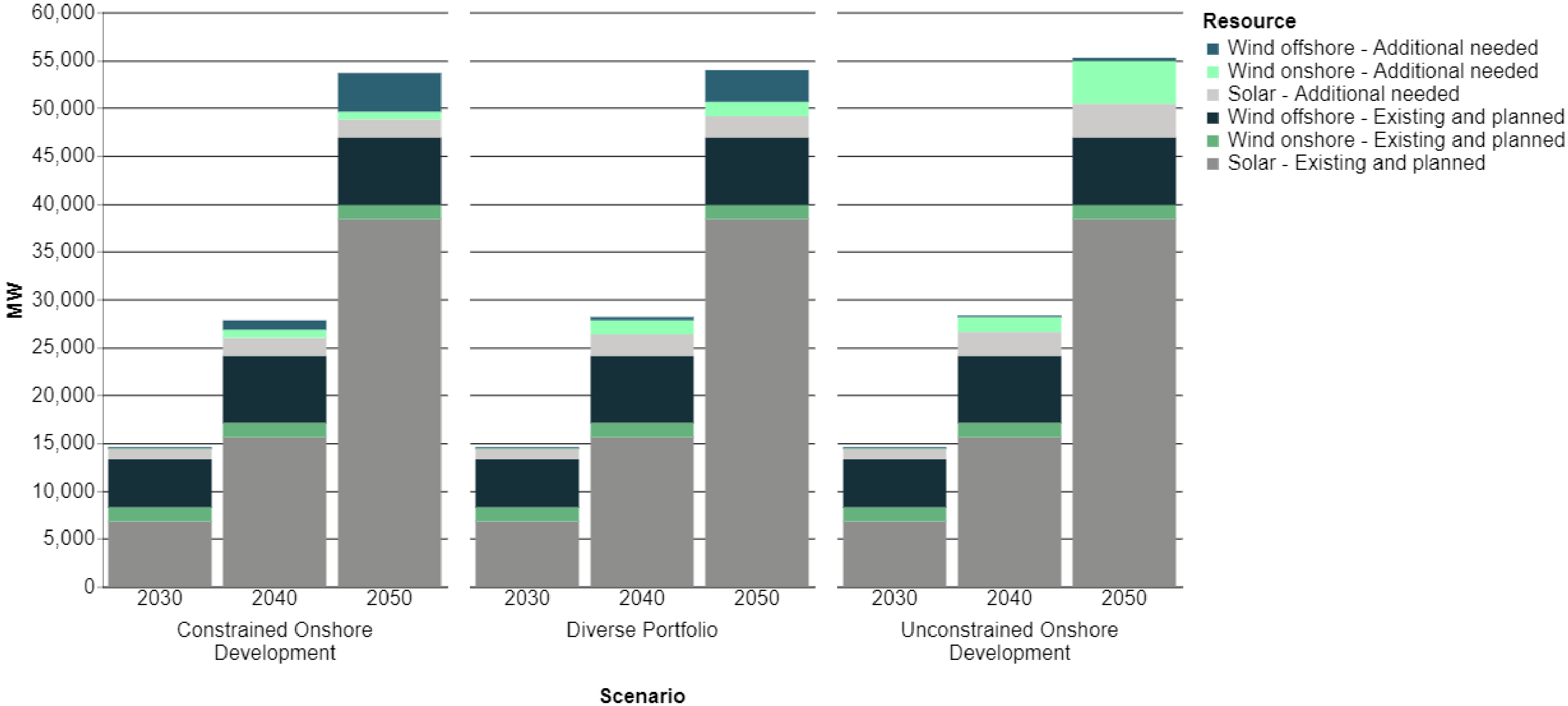
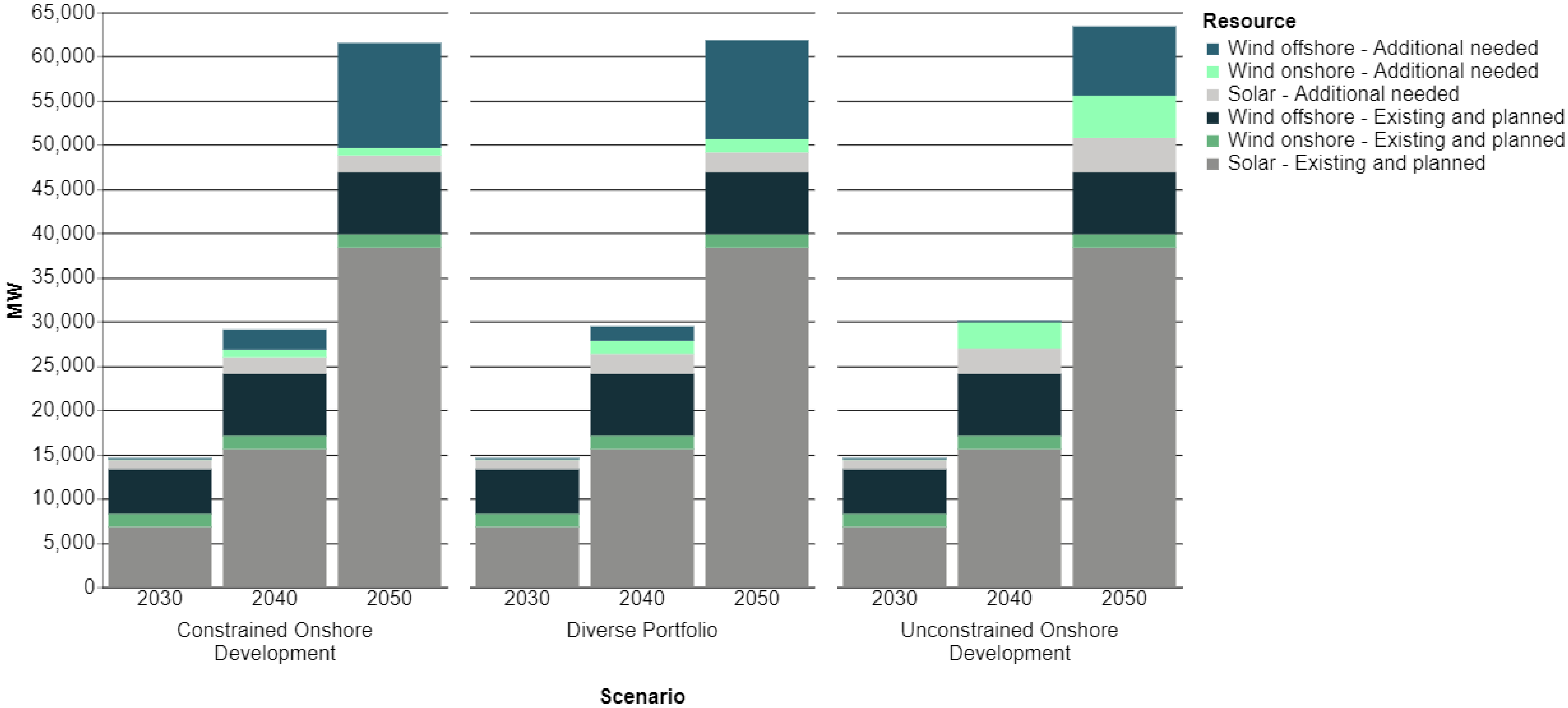


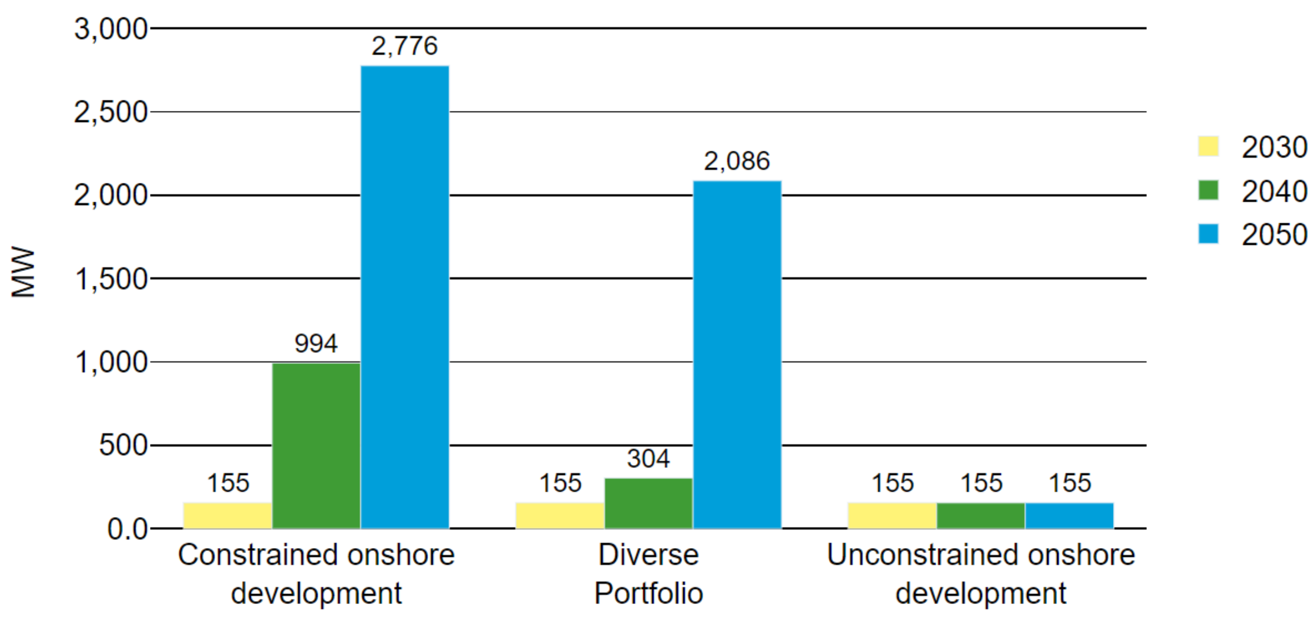
Figure 5-12. New England total resource projections for supply scenarios, decarbonization demand



6 CONCLUSIONS

This offshore wind energy needs assessment examines six scenarios under which offshore wind may be developed in the Gulf of Maine to meet the renewable energy goals and requirements of Maine and other New England states in the years leading up to 2050. The first important takeaway from this analysis is that offshore wind in the Gulf of Maine will employ floating technology, which will be cost-competitive with bottom-fixed technology by 2030. The second is that the development and regulatory timeline mean that only 155 MW of offshore wind will be built in the Gulf of Maine by 2030, and large-scale development is not likely to be completed until the early 2030s. For offshore wind to be built in the Gulf of Maine on this most-aggressive 7-10-year timeline, the infrastructure for planning, permitting, and construction will need to be in place and ready when called upon [27]. This analysis first considered the question of how much offshore wind would be needed to meet net annual Maine electricity demand from renewable resources through 2050 under the decarbonization goals of the Maine Climate Council. Three scenarios were considered, with varying levels of new onshore resources and transmission development permitted. In a scenario with unconstrained onshore development, Maine would be able to meet all of its in-state renewable electricity needs through 2050 with significant onshore generation and transmission construction. In this scenario, we project only the research array and Monhegan demonstration offshore wind installations are built. In the other two scenarios modeled, onshore transmission construction is limited (Diverse Portfolio and Constrained onshore development). In these cases, Maine will need energy from offshore wind to meet its decarbonization goals. These scenarios require between 2-3 GW of offshore wind installations to meet Maine's needs. Figure 6-1 shows how the need for offshore wind to serve Maine's needs is projected to grow over time.

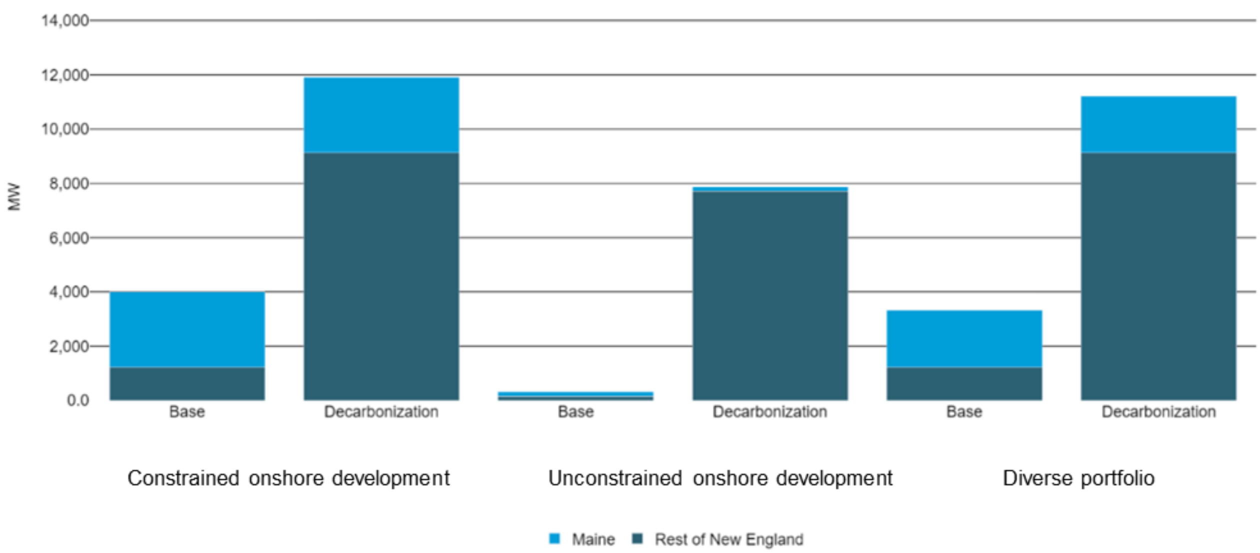
Figure 6-1. Offshore Wind Projections for Maine Scenarios (2030, 2040, 2050)



The analysis also explored how Maine renewable generation resources—both onshore and in the Gulf of Maine—may be able to serve New England's projected rapidly growing demand for renewable energy that cannot be met elsewhere. At the New England level, the analysis explored both a base and high decarbonization demand scenario for renewable electricity demand for the region. These region-level demand scenarios were combined with the three Maine-specific resource constraint scenarios to yield six overall scenarios for how Maine renewables could serve the regional need, after accounting for other regional renewable generation planned outside of Maine. In any scenario, the models predicted that New England states would look to the Gulf of Maine for significant amounts of renewable electricity from offshore wind. In addition, if available, onshore renewables in Maine have high potential to serve the regional generation need.

In the base demand scenario, New England is predicted to look to the Gulf of Maine for between 317 MW and 4 GW of offshore wind by 2050, depending on the extent to which it can access other onshore renewable resources. In the high decarbonization demand scenario, the model expects New England to seek between about 8 and 12 GW of offshore wind development in the Gulf of Maine by 2050. Figure 6-2 shows the total amount of offshore wind developed in each of these scenarios by 2050, and the amount predicted to serve Maine and the rest of New England.

Figure 6-2. Offshore wind projections for Maine and rest of New England (2050)



In this analysis, we also examined, on an average level, how hourly demand and supply compare throughout the year (see APPENDIX C). On the hourly and seasonal level, we see that wind and solar are complementary resources: wind generates more in winter, solar more during summer. Additionally, wind tends to generate more at night, when solar is inactive. Solar, however, generates energy every day, whereas wind lulls can result in no wind energy generation. These hourly variations in generation also highlight the need for storage.

6.1 Comparisons to previous work

While this analysis approached the estimation of offshore wind deployment in New England differently than other reports, it can still be useful to compare results. The Massachusetts *2050 Decarbonization Roadmap* anticipates New England's overall offshore wind capacity growing to between 19.3 and 36.5 GW by 2050 [48]. This is anticipated to include floating offshore wind capacity ranging from 10.1 GW in an offshore wind constrained pathway to 26.8 GW in a limited efficiency pathway, with most built after 2035 [37]. *Net-Zero New England: Ensuring Electric Reliability in a Low-Carbon Future* estimates 22 GW of offshore wind in 2050 [53], and *Achieving 80% GHG Reduction in New England by 2050* estimates 41-43 GW [52].

Our scenarios show between 0.32 and 11.9 GW of offshore wind in the Gulf of Maine, in addition to the 7 GW assumed built by other states for total predictions between 7.3 and 18.9 GW in 2050. These are significantly lower than the Massachusetts and Brattle reports, and somewhat lower than the E3/EFI estimates. One reason for the difference is that our analysis focuses on filling net annual need for renewable energy, as opposed to hourly needs. Additionally, this is a complex prediction with many uncertain variables. Offshore wind is an emerging technology with uncertainty in development timelines and costs; other electricity generation technologies face uncertainty in permitting, approval of transmission for different types of generation can be challenging; and projections about the electrification process and future electricity demand vary. Therefore, variation in predictions between research teams is expected.

Throughout this report, the results demonstrate the interconnectedness of electrification and offshore wind activities in the New England region, and the importance of comprehensive energy planning to efficiently achieve Maine's 100% renewable energy goal. This highlights the need for future research to consider these factors, not just in quantifying state and regional energy needs, but also in obtaining long-term renewable energy projections for the region.

6.2 Recommendations for future work

This work is just one step in the continuing research on offshore wind needs that will need to be conducted as New England decarbonizes. Future work must take into account new developments as well as elements that this research did not address. The first of these is the need for electricity supply to meet demand in real time. Whereas this study only considers meeting the total annual need from total annual renewable generation, as the region increases the fraction of electricity demand served by renewables, the real-time ability of these renewable resources to serve need will be critical. This will involve assessing how demand is likely to vary throughout the year, how that variation might change, and how it might be different in different years. The same analysis will be necessary on the generation side. These analyses will need to be compared to help determine the best mix of renewable generation types. This comparison will also yield information to allow construction of a reliable grid that meets capacity requirements.

Additionally, this analysis does not address energy storage and its potential roles and limitations in grid and load management. The costs, limitations, strengths, and weaknesses of different storage technologies, and the costs and benefits of choosing storage versus additional generation should be examined. Hydrogen production is also not discussed in this report. While not, at the time of this report, an economical storage solution, the need for and complexities around producing hydrogen may need to be considered in the future.

This research estimates the offshore wind and other renewables need at discrete time points (2030, 2040, and 2050) to meet the continuously growing need for additional electricity. However, renewable generation is built in a stepwise fashion: as each additional project becomes operational, generation will increase by the full capacity of the project all at once. As projects are developed and the size of each development is better understood, this stepwise character of adding generation can be added to needs modeling.

Finally, the inputs used in this model, including demand projections and costs of renewable generation (especially for floating offshore wind) are all uncertain. Future work should update this data frequently to provide ever-more-accurate predictions.

With a significant amount of technical energy potential in the Gulf of Maine, the State of Maine's primary challenge is to create an environment that fosters the development of a floating offshore wind industry in Maine that includes policies and incentives that lower the LCOE to attract investment into Maine and maximize the benefits to Maine people. This primary challenge is the impetus for further studies to be carried out evaluating the socio-economic impacts of each of these scenarios, deployment strategies that maximize benefits to Maine people, and transmission strategies for floating offshore wind in Maine that ensure a balanced approach to providing affordable, reliable, renewable electricity to Maine and the rest of the region.

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[60]	ISO-NE. Net Energy and Peak Load by Source file. https://www.iso-ne.com/static-assets/documents/2022/02/2022_energy_peak_by_source.xlsx
[61]	ISO-NE. Maine Resource Integration Study Report. https://www.iso-ne.com/static-assets/documents/2018/03/final_maine_resource_integration_study_report_non_ceii.pdf
[62]	NREL. Annual Technology Baseline Definitions. Definitions | Electricity | 2021 | ATB | NREL
[63]	DNV. Offshore Wind Transmission Technical Review – Initial Report. Sponsored by the Maine Governor's Energy Office and Maine Offshore Wind Roadmap. https://www.maine.gov/energy/sites/maine.gov.energy/files/inline-files/Maine%20OSW%20DNV%20Offshore%20Wind%20Transmission%20Technical%20Review%20Initial%20Report.pdf

APPENDIX A. OFFSHORE WIND DEVELOPMENT POTENTIAL

To determine offshore wind development potential, DNV conducted a secondary literature review of the following data to understand key policies and regulations influencing offshore wind development, offshore wind technical potential in the Gulf of Maine, the trajectory of offshore wind cost and technological maturity, and offshore wind development and goals in other states and countries. This information informed the assumptions described in Section 3.2.

- Global: DNV 2021 Energy Transition Outlook
- United Kingdom: The Ten Point Plan for a Green Industrial Revolution
- National: 2016 Offshore Wind Energy Resource Assessment for the United States
- Regional: Massachusetts Energy Pathways to Deep Decarbonization
- Other Floating Offshore Wind Market: California's Offshore Wind Electricity Opportunity
- Other Floating Offshore Wind Market: State of Oregon Floating Offshore Wind Study
- State: Floating Offshore Wind in Maine - Advanced Structures & Composites Center - University of Maine
- State: Offshore Wind Resource, Cost, and Economic Potential in the State of Maine

APPENDIX B. NEW ENGLAND GROSS OFFSHORE WIND POTENTIAL [11]

Table 7-1. New England: gross offshore wind potential by water depth: area (km²)

	Maine		New Hampshire		Vermont		Massachusetts		Rhode Island		Connecticut	
Depth	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**
< 30 m	4,797	11%	146	21%	0	0%	10,828	6%	1,078	15%	1,224	80%
30-60 m	2,773	7%	143	20%	0	0%	25,182	14%	2,480	35%	263	17%
60-700 m	**34,939**	82%	**416**	59%	0	0%	**57,507**	32%	2,916	41%	40	3%
700 – 1000m	0	0%	0	0%	0	0%	**2,014**	1%	139	2%	0	0%
> 1000 m	0	0%	0	0%	0	0%	**86,411**	47%	470	7%	0	0%
Total	**42,509**		**706**		**0**		**181,943**		**7,083**		**1,527**	

* Floating offshore is considered technically viable in water depths of 50 to 1,500 m. Projects over 1,000 m are technically viable, though higher LCOE.

Table 7-2. New England: gross offshore wind potential by distance from shore: area (km²)

	Maine		New Hampshire		Vermont		Massachusetts		Rhode Island		Connecticut	
Distance	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**
< 3 nm	6,404	15%	187	26%	0	0%	5,531	3%	929	13%	1,527	100%
3-12 nm	7,946	19%	365	52%	0	0%	7,087	4%	1,527	22%	0	0%
12-50 nm	18,843	44%	153	22%	0	0%	27,568	15%	2,788	39%	0	0%
50-200 nm	9,316	22%	0	0%	0	0%	141,757	78%	1,839	26%	0	0%
Total	**42,509**		**706**		**0**		**181,943**		**7,083**		**0**	

* State waters distanced 3 nm from coastal shore

Table 7-3 New England: Gross offshore wind potential by wind speed: area (km²)

	Maine		New Hampshire		Vermont		Massachusetts		Rhode Island		Connecticut	
Speed	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**	**MW**	**% Total**
< 7 m/s	411	1%	25	4%	0	0%	29	0%	63	1%	154	10%
< 7-7.25 m/s	417	1%	8	1%	0	0%	76	0%	96	1%	156	10%
< 7.25-7.5 m/s	502	1%	8	1%	0	0%	116	0%	171	2%	217	14%
< 7.5-7.75 m/s	589	1%	22	3%	0	0%	211	0%	59	1%	458	30%
< 7.75-8 m/s	585	1%	25	4%	0	0%	331	0%	74	1%	373	24%
< 8-8.25 m/s	758	2%	31	4%	0	0%	517	0%	147	2%	170	11%
< 8.25-8.5 m/s	1,080	3%	88	12%	0	0%	1,082	1%	170	2%	0	0%
< 8.5-8.75 m/s	1,237	3%	142	20%	0	0%	1,777	1%	259	4%	0	0%
< 8.75-9 m/s	1,647	4%	202	29%	0	0%	2,316	1%	563	8%	0	0%
< 9-9.25 m/s	2,385	6%	129	18%	0	0%	3,112	2%	533	8%	0	0%
< 9.25-9.5 m/s	5,731	`3%	25	4%	0	0%	28,179	15%	4,917	69%	0	0%
< 9.5-9.75 m/s	13,918	33%	0	0%	0	0%	92,826	51%	32	0%	0	0%
< 9.75-10 m/s	8,749	21%	0	0%	0	0%	51,370	28%	0	0%	0	0%
< 10-10.25 m/s	4,499	11%	0	0%	0	0%	0	0%	0	0%	0	0%
< 10.25-11.5 m/s	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
Total	**42,509**		**706**		**0**		**181,943**		**7,083**		**1,527**	

APPENDIX C. DATA VIZUALIZATION OF NET RENEWABLE SHORT

The following three figures show the data and process used to calculate the renewable net short, the potential of Maine's renewable resources to fill that shortage, and the average time and season when demand and generation are high or low.

The first row of graphs shows the projected demand and availability of renewable resources. In the hourly graphs (showing the hours of the year during which the summer and winter demand maximums, or peaks, occur), there are three lines showing the projected load shape, or hourly renewable demand, in 2030, 2040, and 2050. These graphs also show how the current and projected renewable generation compares to that projected need. In Maine, that current renewable generation is lower, at every hour, than the projected hourly renewable need. At the New England level, the graph shows not only existing renewable generation, but projected renewable generation. However, these lines appear as one thick line, because the projections are limited in time and scale; the total projected renewable resource amount is similar for 2030-2050. At the New England level, the current renewables are able to cover some hours of demand in 2030 (and in the low-demand scenario, in 2040). The far-right plot in the first row of graphs shows the total annual renewable electricity demand and the total annual renewable supply by resource type. The total height of the bars in each graph is the renewable electricity demand in that year, and the difference between the sum of the renewable supply in that year and the demand is the total renewable net short.

The second row of graphs shows the shortage in renewable generation. The two left-side graphs show this shortage on the hourly level, with different lines for 2030, 40, and 50. The far-left shows this shortage during high-demand winter days, and the center graph shows high-demand summer days. These graphs also have a line showing the total potential for as-yet-untapped renewable generation in Maine to fulfill this demand. It is important to note that this is just the average likely time when this renewable generation would occur. In any given year, there will be certain hours with wind lulls and others with intense wind. Energy storage will be necessary to overcome this challenge.

The far right graph in the second row shows the shortages on a net basis: total renewable need in these future years, less the amount that will be generated by current or projected renewable resources.

Finally, the bottom row of these graphs shows the potential for each as-yet-untapped renewable resource in Maine to fill demand needs, on both an hourly and annual basis. The hourly graphs here are a twenty-year average of hourly generation, so do not show events like wind lulls. On the hourly and seasonal level, we see that wind and solar are complementary resources: wind generates more in winter, solar more during summer. Additionally, wind tends to generate more at night, when solar is inactive. Solar, however, generates energy every day, whereas wind lulls can result in no wind energy generation. These hourly variations in generation also highlight the need for storage. From the total-generation perspective, we see that offshore wind has a greater amount of feasible capacity available than all other resources, and could serve a large part of New England's demand, even in a high-demand scenario. However, it is important to note that floating offshore wind in the Gulf of Maine will likely not begin at scale for a decade at the earliest, so other resources need to be developed to meet Maine's needs as the floating offshore wind industry is established. Resource costs and Maine values around each resource will also be important considerations.

Figure 7-1. Renewable Supply and Demand, Maine Only

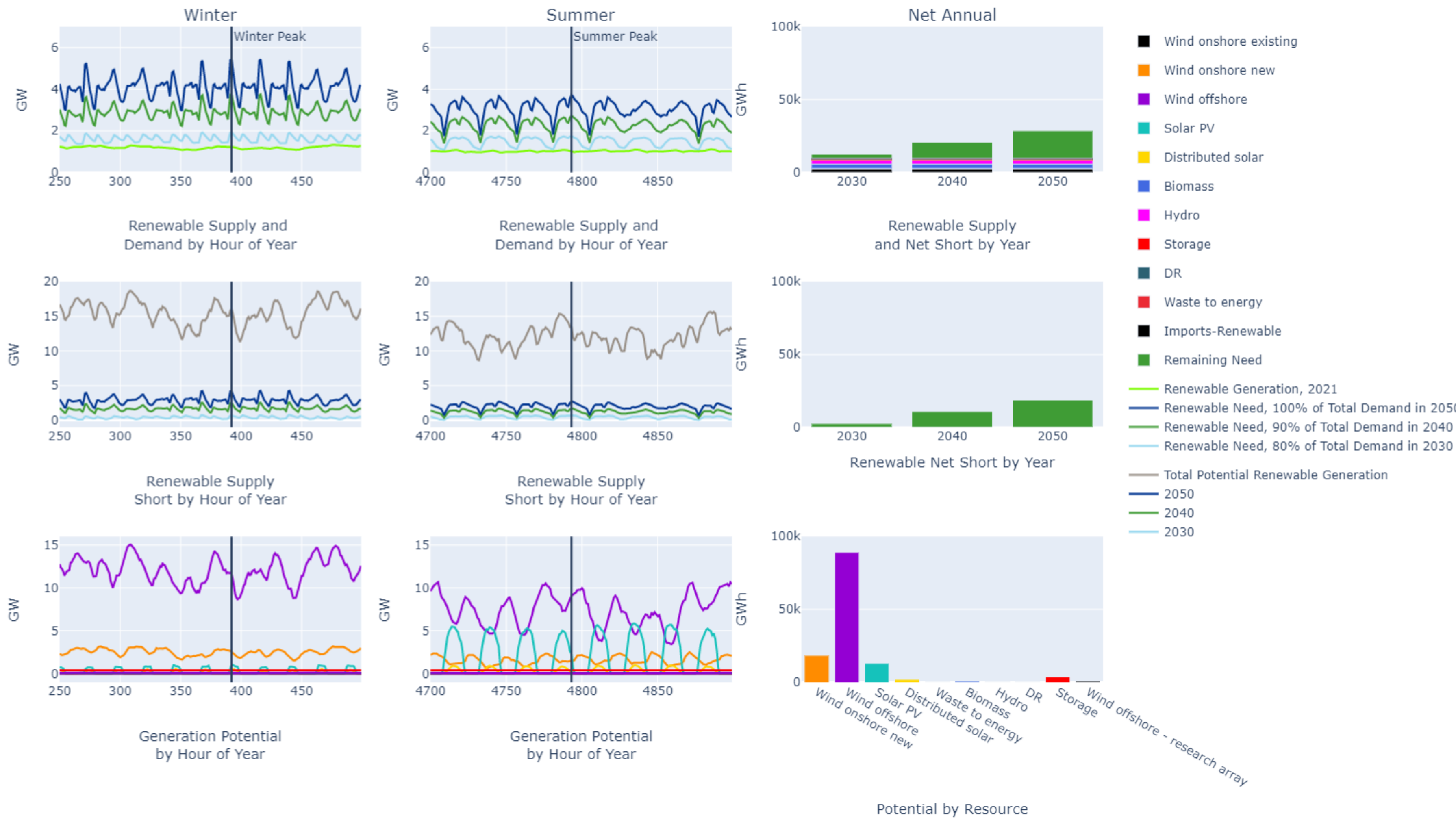


Figure 7-2. Renewable Supply and Demand, New England, Low Demand Scenario

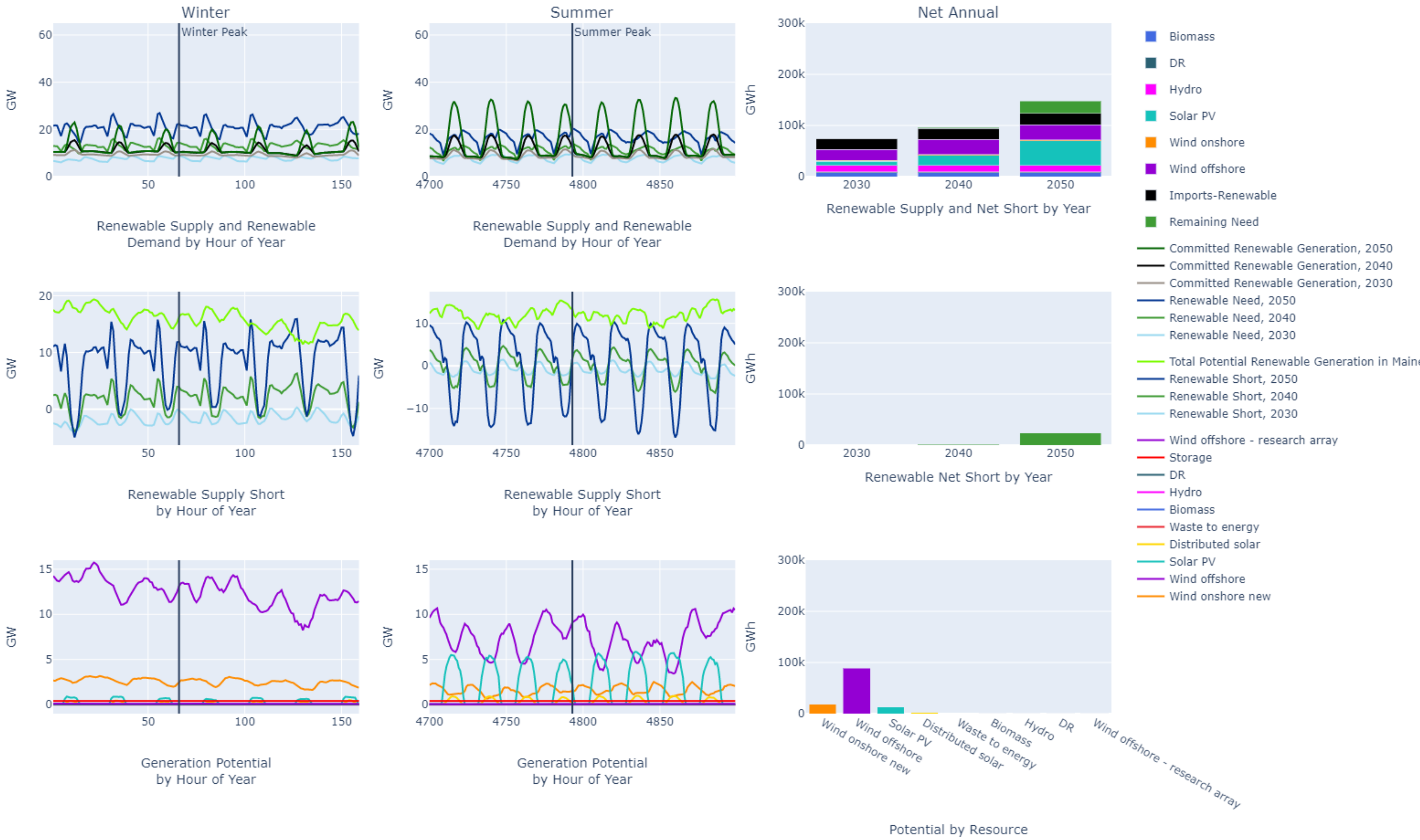
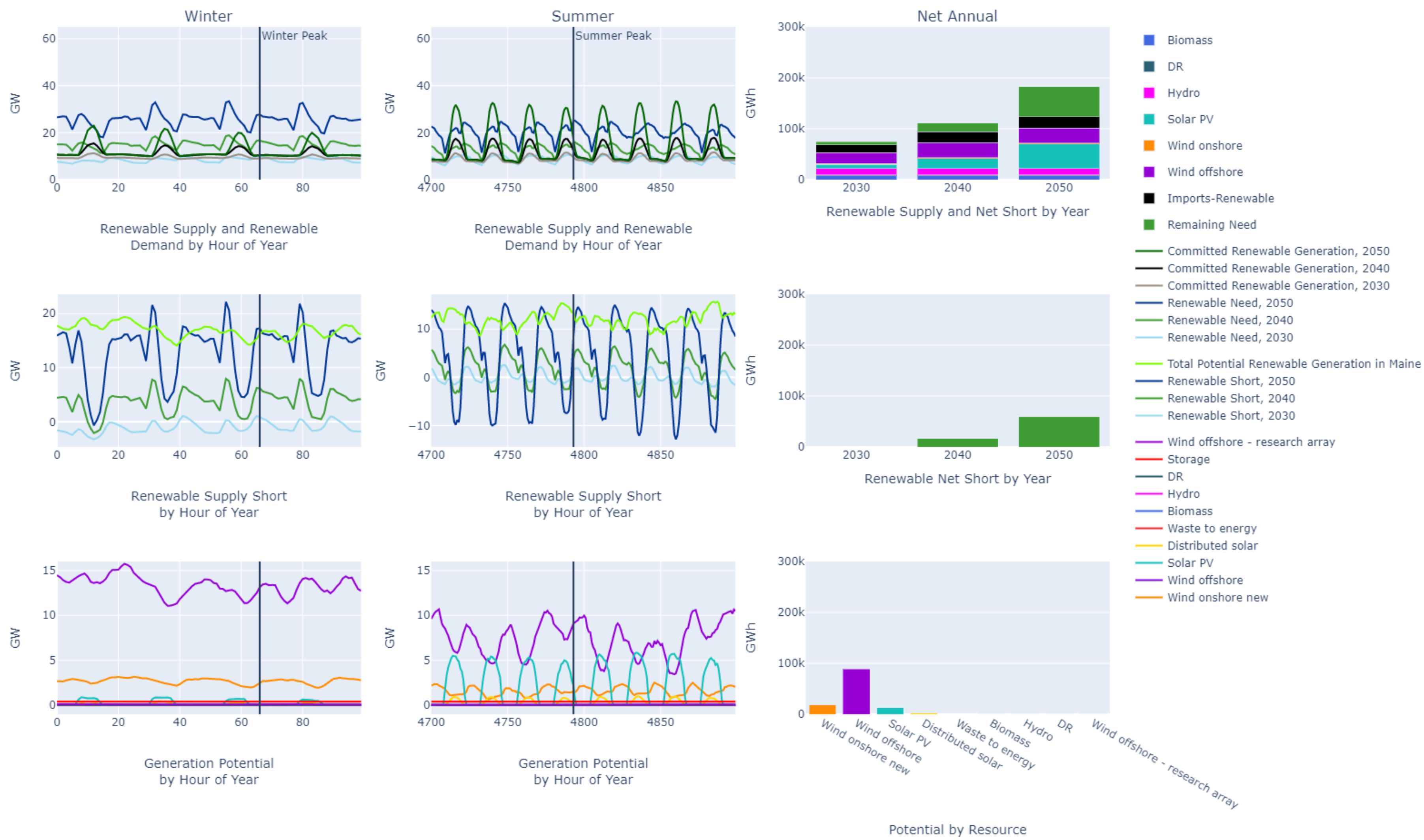


Figure 7-3. Renewable supply and demand, New England, decarbonization demand scenario



APPENDIX D. SCENARIO RESULTS: ENERGY NEEDS PROJECTIONS

This appendix presents the projections of energy needs by resource for each scenario.

Table 7-4. Matrix of demand and supply scenarios

		Supply		
		Constrained onshore development	Unconstrained onshore development	Diverse Portfolio
New England Demand	Base Case Demand	1	3	5
	Decarbonization Demand	2	4	6

Table 7-5. Scenario 1 projections of energy needs (MWh) by resource for Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,592,781	3,111,002	3,111,002	1,592,781	3,111,002	3,111,002
Onshore wind	187,270	3,029,284	3,029,284	187,270	3,029,284	3,029,284
Offshore wind	694,617	4,458,375	12,442,078	694,617	4,458,375	17,936,356

Figure 7-4. Scenario 1 energy projections (GWh) for Maine and New England

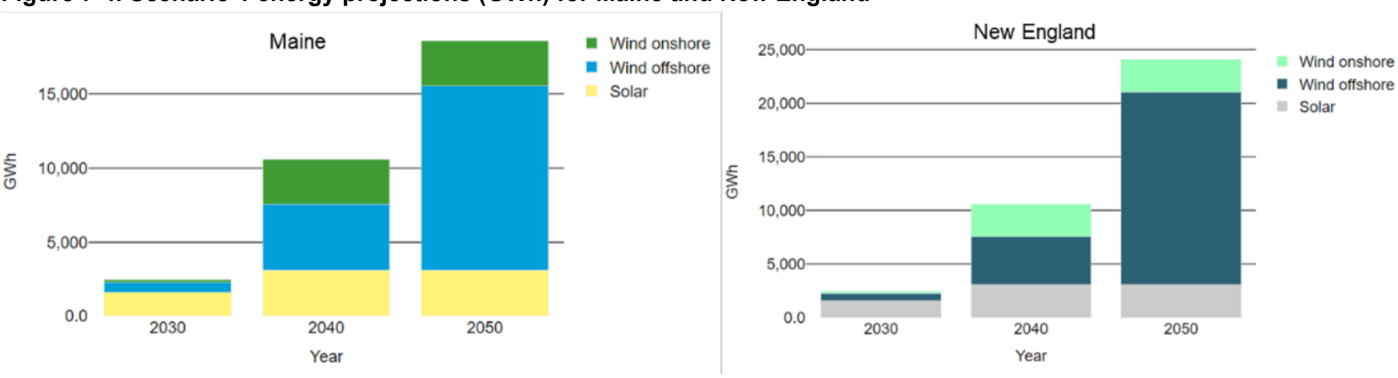


Table 7-6. Scenario 2 projections of energy needs (MWh) by resource for Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,592,781	3,111,002	3,111,002	1,592,781	3,111,002	3,111,002
Onshore wind	187,270	3,029,284	3,029,284	187,270	3,029,284	3,029,284
Offshore wind	694,617	4,458,375	12,442,078	694,617	10,350,697	53,355,085

Figure 7-5. Scenario 2 energy projections (GWh) for Maine and New England

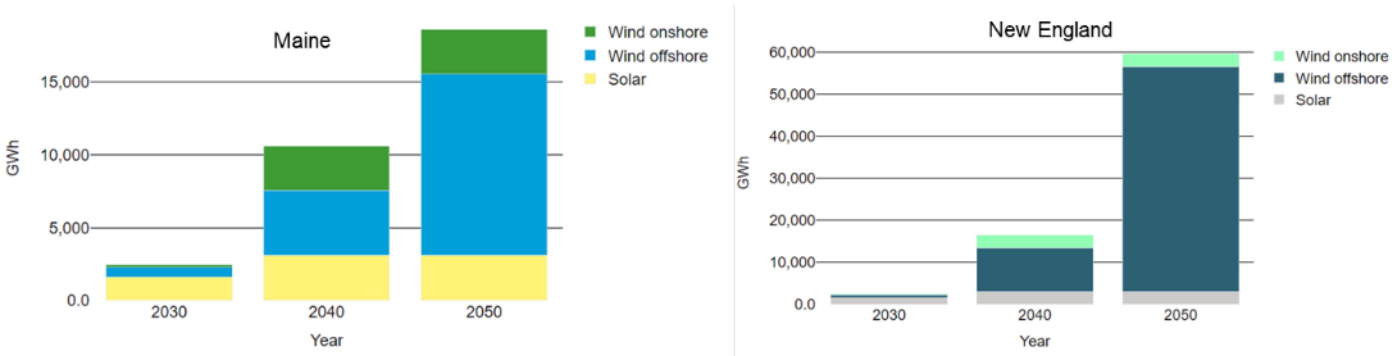


Table 7-7. Scenario 3 projections of energy needs (MWh) by resource for Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,592,781	4,195,084	4,845,660	1,592,781	4,195,084	6,146,811
Onshore wind	187,270	5,708,959	13,042,087	187,270	5,708,959	16,509,357
Offshore wind	694,617	694,617	694,617	694,617	694,617	1,420,472

Figure 7-6. Scenario 3 energy projections (GWh) for Maine and New England

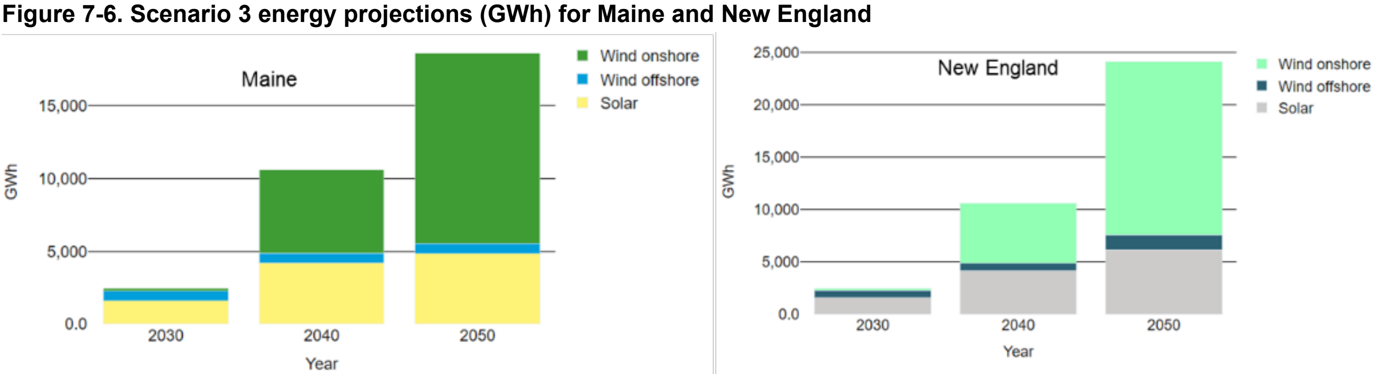


Table 7-8. Scenario 4 projections of energy needs (MWh) by resource for Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,592,781	4,195,084	4,845,660	1,592,781	4,845,660	6,797,387
Onshore wind	187,270	5,708,959	13,042,087	187,270	10,950,705	17,426,544
Offshore wind	694,617	694,617	694,617	694,617	694,617	35,271,440

Figure 7-7. Scenario 4 energy projections (GWh) for Maine and New England

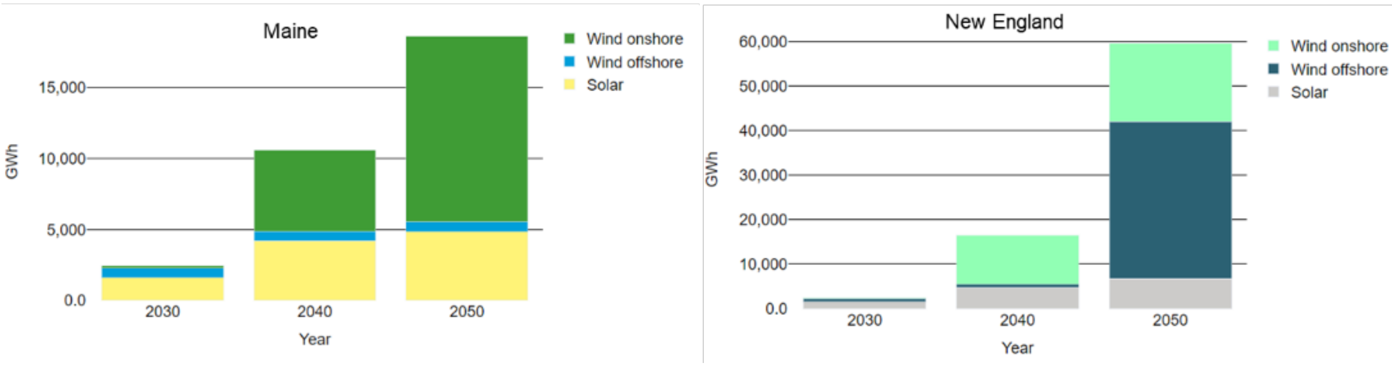


Table 7-9. Scenario 5 projections of energy needs (MWh) by resource for Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,592,781	3,730,387	3,730,387	1,592,781	3,730,387	3,730,387
Onshore wind	187,270	5,503,119	5,503,119	187,270	5,503,119	5,503,119
Offshore wind	694,617	1,365,154	9,348,858	694,617	1,365,154	14,843,135

Figure 7-8. Scenario 5 energy projections (GWh) for Maine and New England

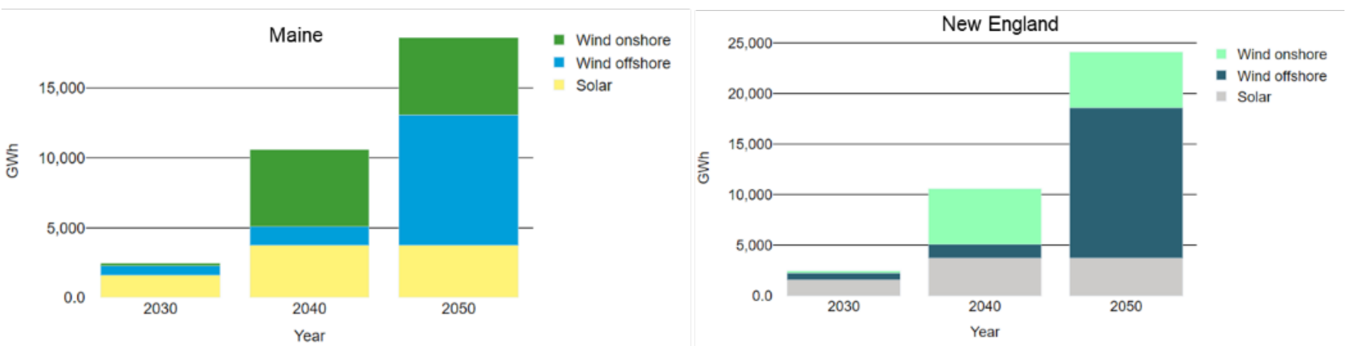
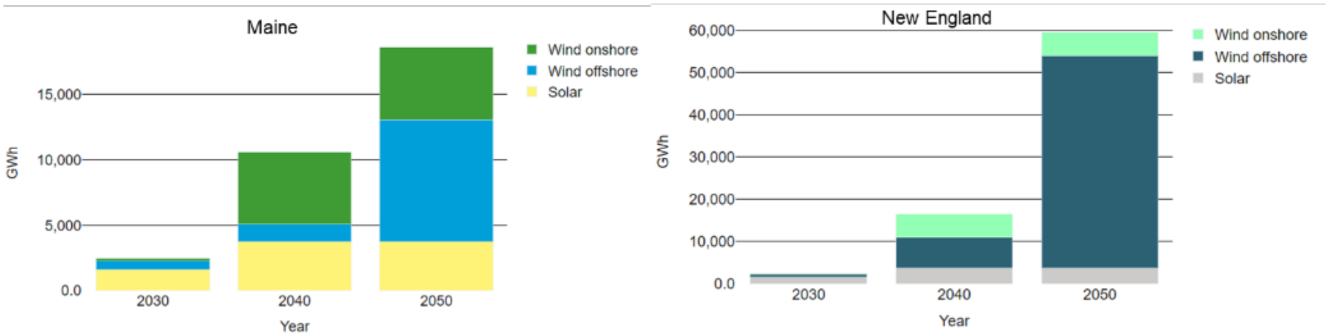


Table 7-10. Scenario 6 projections of energy needs (MWh) by resource for Maine and New England demand

Resource	Maine			New England		
	2030	2040	2050	2030	2040	2050
Solar PV	1,592,781	3,730,387	3,730,387	1,592,781	3,730,387	3,730,387
Onshore wind	187,270	5,503,119	5,503,119	187,270	5,503,119	5,503,119
Offshore wind	694,617	1,365,154	9,348,858	694,617	7,257,476	50,261,864

Figure 7-9. Scenario 6 energy projections (GWh) for Maine and New England



APPENDIX E. COMBINED RESOURCE CAPACITY AND ENERGY PRODUCTION TABLES

Table 7-11. Maine-only capacity and energy by resource

Scenario	Year	Resource	Capacity Upgrade (MW)	MWh
Constrained Onshore Development (#1 & #2)	2030	Solar PV	1,100	1,592,781
	2030	Wind onshore	51	187,270
	2030	Wind offshore	155	694,617
	2040	Solar PV	1,917	3,111,002
	2040	Wind onshore	826	3,029,284
	2040	Wind offshore	995	4,458,375
	2050	Solar PV	1,917	3,111,002
	2050	Wind onshore	826	3,029,284
	2050	Wind offshore	2,776	12,442,078
Unconstrained Onshore Development (#3 & #4)	2030	Solar PV	1,100	1,592,781
	2030	Wind onshore	51	187,270
	2030	Wind offshore	155	694,617
	2040	Solar PV	2,500	4,195,084
	2040	Wind onshore	1,556	5,708,959
	2040	Wind offshore	155	694,617
	2050	Solar PV	2,850	4,845,660
	2050	Wind onshore	3,555	13,042,087
	2050	Wind offshore	155	694,617
Diverse Portfolio (#5 & #6)	2030	Solar PV	1,100	1,592,781
	2030	Wind onshore	51	187,270
	2030	Wind offshore	155	694,617
	2040	Solar PV	2,250	3,730,387
	2040	Wind onshore	1,500	5,503,119
	2040	Wind offshore	305	1,365,154
	2050	Solar PV	2,250	3,730,387
	2050	Wind onshore	1,500	5,503,119
	2050	Wind offshore	2,086	9,348,858

Table 7-12. All New England capacity and output by resource

Scenario	Demand Scenario	Year	Resource	Capacity Upgrade (MW)	MWh
Constrained Onshore Development	Base Demand (#1)	2030	Solar PV	1,100	1,592,781
		2030	Wind onshore	51	187,270
		2030	Wind offshore	155	694,617
		2040	Solar PV	1,917	3,111,002
		2040	Wind onshore	826	3,029,284
		2040	Wind offshore	995	4,458,375
		2050	Solar PV	1,917	3,111,002
		2050	Wind onshore	826	3,029,284
		2050	Wind offshore	4,002	17,936,356
	Decarbonization Demand (#2)	2030	Solar PV	1,100	1,592,781
		2030	Wind onshore	51	187,270
		2030	Wind offshore	155	694,617
		2040	Solar PV	1,917	3,111,002
		2040	Wind onshore	826	3,029,284
		2040	Wind offshore	2,310	10,350,697
		2050	Solar PV	1,917	3,111,002
		2050	Wind onshore	826	3,029,284
		2050	Wind offshore	11,906	53,355,085
Unconstrained Onshore Development	Base Demand (#3)	2030	Solar PV	1,100	1,592,781
		2030	Wind onshore	51	187,270
		2030	Wind offshore	155	694,617
		2040	Solar PV	2,500	4,195,084
		2040	Wind onshore	1,556	5,708,959
		2040	Wind offshore	155	694,617
		2050	Solar PV	3,550	6,146,811
		2050	Wind onshore	4,500	16,509,357
		2050	Wind offshore	317	1,420,472
	Decarbonization Demand (#4)	2030	Solar PV	1,100	4,845,660
		2030	Wind onshore	51	10,950,705
		2030	Wind offshore	155	694,617
		2040	Solar PV	2,850	6,797,387
		2040	Wind onshore	2,985	17,426,544
		2040	Wind offshore	155	35,271,440
		2050	Solar PV	3,900	13,012
		2050	Wind onshore	4,750	18,344
		2050	Wind offshore	7,871	89,628
Diverse Portfolio	Base Demand (#5)	2030	Solar PV	1,100	1,592,781
		2030	Wind onshore	51	187,270

Scenario	Demand Scenario	Year	Resource	Capacity Upgrade (MW)	MWh
		2030	Wind offshore	155	694,617
		2040	Solar PV	2,250	3,730,387
		2040	Wind onshore	1,500	5,503,119
		2040	Wind offshore	305	1,365,154
		2050	Solar PV	2,250	3,730,387
		2050	Wind onshore	1,500	5,503,119
		2050	Wind offshore	3,312	14,843,135
	Decarbonization Demand (#6)	2030	Solar PV	1,100	1,592,781
		2030	Wind onshore	51	187,270
		2030	Wind offshore	155	694,617
		2040	Solar PV	2,250	3,730,387
		2040	Wind onshore	1,500	5,503,119
		2040	Wind offshore	1,619	7,257,476
		2050	Solar PV	2,250	3,730,387
		2050	Wind onshore	1,500	5,503,119
		2050	Wind offshore	11,216	50,261,864

About DNV

DNV is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable our customers to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter and greener.