Maine Offshore Wind Analysis

State of the Offshore Wind Industry: Today through 2050

State of Maine Governor's Energy Office

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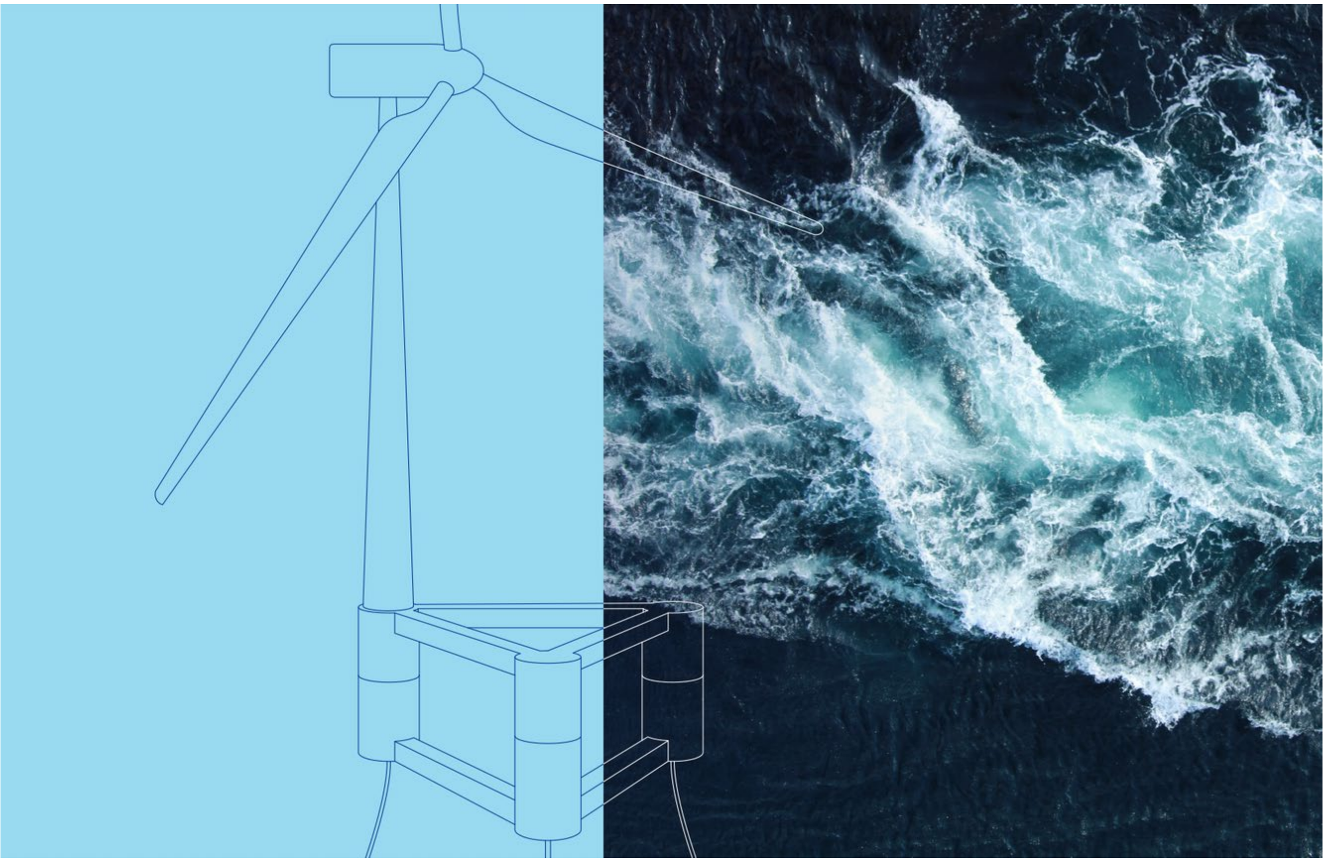

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Table 1-1. Abbreviations

Abbreviations	
BOEM	Bureau of Ocean Energy Management
CAPEX	Capital Expenditures
CCS	Carbon capture and storage
CHN	China
COP	Construction and operation plan
DOE	Department of Energy
DNV	Det Norske Veritas
EPC	Engineering, procurement, and construction
ETO	Energy Transition Outlook
EUR	Europe
EV	Electrical vehicle
FEED	Front-end engineering design
FID	Final investment decision
GWEC	Global Wind Energy Council
IAC	Inter-array cable
IND	Indian Subcontinent
LAM	Latin America
LCOE	Levelized Cost of Energy
MEA	Middle East and North Africa
NAM	North America
NEE	North East Eurasia
NREL	National Renewable Energy Laboratory
OPA	OECD Pacific
OPEX	Operating Expenditures
ORE	Offshore Renewable Energy
OSW	Offshore wind
O&M	Operation and Maintenance
R&D	Research and development
SSA	Sub-Saharan Africa
SEA	South East Asia
TRL	Technology readiness level (method for estimating the maturity of technologies)
US	United States
WFO	World Forum Offshore Wind
WTG	Wind turbine generator

Table 1-2. Units

Units	
ft	feet
GW	Gigawatt
kW	Kilowatt
kWh	Kilowatt hour
m	Meters
MW	Megawatt
MWh	Megawatt hour
Nm	Nautical miles

Units	
Sq mi	Square miles
TW	Terawatt
TWh	Terawatt hour
yr	Year
trn	Trillion
PJ	Petajoule

1 EXECUTIVE SUMMARY

The wind energy sector currently accounts for a total worldwide installed capacity of 745 GW and it is forecasted to experience steady growth over the next decades, including offshore wind in both fixed-bottom and floating configurations. Today, the offshore wind industry includes projects that make up only about 5% of total offshore wind capacity worldwide. However, upwards of 1,500 GW of fixed-bottom offshore wind and 250 GW of floating wind are forecasted to be installed by 2050, based on DNV's Energy Transition Outlook 2021 [1]. This implies a total share of 45% for wind energy, with 27% coming from onshore wind, 13% from fixed-bottom and 5% from floating wind technologies. For floating wind, this is projected to include an 80% reduction in the levelized cost of energy (LCOE) from its current value, compared to a 44% reduction in LCOE for fixed-bottom offshore wind.

In the United States (US), the current share of total installed onshore and offshore wind capacity is lower than in other global regions such as Europe; nonetheless, the United States (US) is identified as a high-potential market based on the combination of its wind resources, coastlines, and water depths (see Section 3.3). Currently, there is 35 GW of potential offshore wind in US project pipelines to be installed between 2027 and 2035, with 12 GW of potential capacity in unleased wind energy areas – areas which have not been awarded to a bidder after the US Bureau of Ocean Energy Management (BOEM) auction process. The early industry phase development in northern Europe has provided a high technology readiness level (TRL; see Appendix B) that makes offshore wind an attractive opportunity for investors and developers and a focus for policymakers seeking technologies to decarbonize the energy mix on a larger scale.

National policy trends feature demands for clean power, including offshore wind; a push to develop decarbonization strategies; growth in workforce development policies supporting offshore wind; and an expansion of the BOEM Federal lease areas. Additionally, state renewable & clean electricity standards, federal tax credits, and the Biden Administration's goals of 100% carbon-free electricity by 2035, 30 GW of offshore wind by 2030, and Paris Commitment to achieve net zero emissions by 2050 are driving demand for decarbonization. Implementing an offshore wind development strategy will help Maine leverage these important national synergies.

While Maine's renewable goal electricity standard is one of the most ambitious in the United States—80% by 2030 with a goal of 100% by 2050—the State currently has no defined offshore wind-specific procurements. Offshore wind energy potential in Maine ranked seventh in wind energy potential – measured as wind speeds over offshore area - in the US and the State has more than 411 TWh/yr of offshore resource-generating potential. Limitations in the Gulf of Maine, including the Gulf of Maine's deep water ocean floor bathymetry [58] and a moratorium on offshore wind development in state waters, can be mitigated by steering development in Maine towards the use of floating wind technologies. Maine has ample potential to support floating offshore wind technologies in deeper federal waters where a State moratorium does not apply. **The floating wind industry segment is therefore considered a high-potential market where Maine can become a major player by leveraging national and regional market trends, technology improvements, and efficiency gains** (see Section 4.2).

The reduction of the LCOE for floating wind can be influenced through a combination of policy changes, infrastructure upgrades, and relevant workforce development. The State of Maine can leverage the current state of the offshore wind industry to become a center of excellence for floating wind technology development, provide ample supply of wind energy both locally and regionally, and help meet its state and regional climate and renewable energy goals in a faster manner through higher output capacity developments than with onshore renewable energy alone. To do so, Maine can consider the following attributes necessary to facilitate floating offshore wind energy growth and economic expansion, while driving down LCOE:

- Policymaking that facilitates the development of floating wind
- Involvement with and implementation of R&D initiatives aimed at tackling the main cost drivers of floating wind

- Development of emerging technologies that potentially complement floating wind, and that increase the capacity of floating offshore wind deployments, mitigate the environmental impacts of deployments, and capture carbon (Section 6)
- Infrastructure, workforce, and supply chain preparation that enables this market to unlock its significant industrialization potential, in addition to the need for transmission-specific infrastructure upgrades
- Supporting the development of a regional industry, by exploring the possibility of cooperative partnerships and/or leveraging development resources with existing and potential offshore wind industry players in the Northeast

2 INTRODUCTION

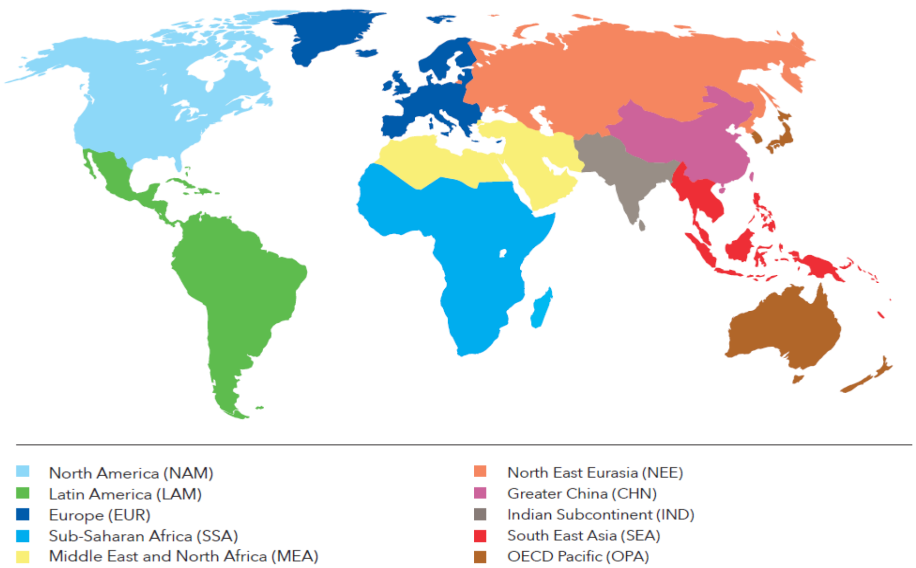
This report encompasses the initial assessment performed by DNV to provide a baseline of trends in the offshore wind industry and provide information on the growing competitiveness of deep-water turbines. The main goals of this assessment are as follows:

- Evaluate global, US, and regional market trends for offshore wind with a specific focus on floating offshore wind, as a key enabler for the deployment of this technology in transitional and deep-water environments.
- Analyze cost trend projections for deep water offshore wind deployments and the associated and emerging technologies in the field.
- Evaluate the industry-wide R&D needs, especially as they relate to the main floating technology cost drivers and determine different potential strategies for Maine to help meet those needs.
- Identify additional emerging technologies and innovations that may complement offshore wind, such as the production of hydrogen; and key opportunities to develop an offshore wind industry in Maine that can support both fixed and floating offshore wind projects.
- Define opportunities for Maine to be a hub for floating offshore wind, including options for technology innovation.

2.1 DNV's Energy Transition Outlook

DNV's Energy Transition Outlook (ETO) [1] is frequently used throughout this report as a reference for predictions about the energy market. The ETO, based on DNV's independent model of the world's energy systems, forecasts the global energy transition from the present to 2050 in 10 different world regions. For this assessment, "North America" comprises the United States and Canada and is frequently used to describe expectations for development in Maine. For the definition of the 10 regions presented by the ETO, see Figure 2-1. The ETO builds on modeling assumptions relevant for different renewable energy sources, which may be different from other outlooks and is thus comparable to other outlooks only to a certain extent.

Figure 2-1. Overview of the 10 regions presented in the 2021 Energy Transition Outlook [1]



The ETO presents a single "best estimate" forecast of the energy future, with sensitivities in relation to the main conclusions. It simulates the interactions over time of energy consumers (transport, buildings, manufacturing, etc.) and all supply sources. Input into the model is historical data back to 1980 and future trends towards 2050. Population changes, GDP per person, and policy drivers are also important input parameters. The model simulates the supply and demand of energy globally on an hourly basis towards 2050. The model outputs estimate for global energy demand, supply, and costs on an annual basis, within the 10 regions, from today until 2050. The ETO is thus well suited to forecast long-term trends in the energy market and the potential for the growth of the market share of renewable energy.

2.2 Report structure

The remainder of this assessment is structured as follows:

- **Section 3 Global, US, and regional market trends for offshore wind** develops a baseline of the global, US and regional offshore wind
- **Section 4 Cost trend projections** further describes trends identified in Section 3 and benchmarks them using ETO insights to describe the LCOE evolution
- **Section 5 Industry-wide R&D needs** outlines the main funding agencies currently focused on floating wind technology innovation and the main fields of evolution, and briefly describes how each of the cost variables are being targeted from a research and development (R&D) standpoint
- **Section 6 Emerging offshore wind industry advancements and innovations** highlights complementary technologies and innovations that can improve the efficiency or output of the offshore wind deployments, and includes new functionalities in the space of offshore wind deployments

3 GLOBAL, US, AND REGIONAL MARKET TRENDS FOR OFFSHORE WIND

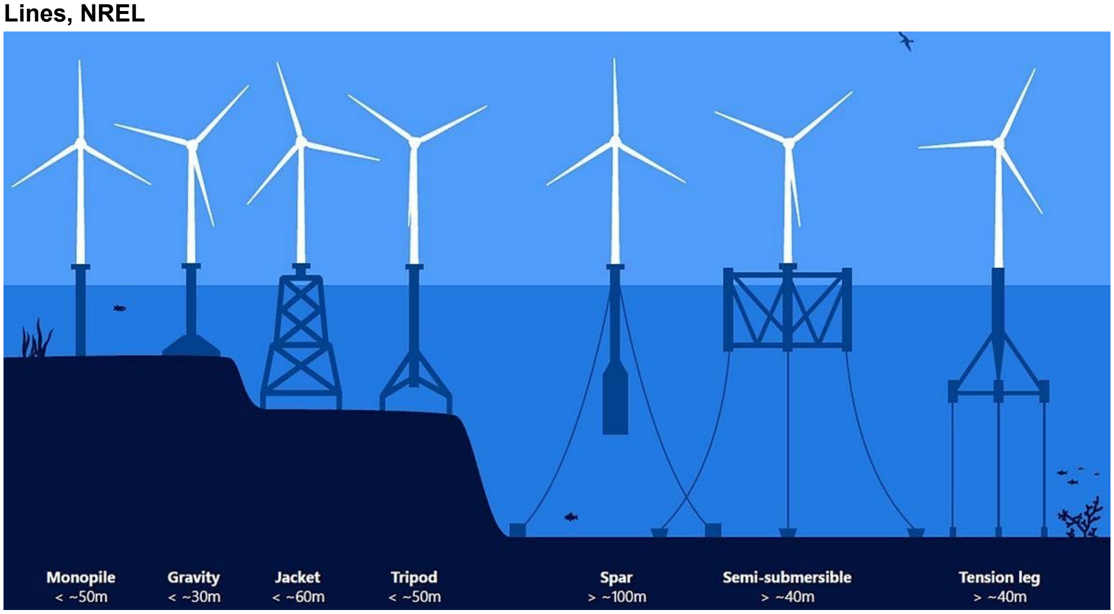
The global, US, and regional Maine market trends for offshore wind are driven to some extent by policy initiatives and other key factors like environmental awareness and the commercialization progress of emerging technologies. The following section explores the status and forecasts of the selected offshore wind markets and highlights the relevant market trends and drivers for offshore wind deployments.

3.1 Floating wind technology introduction: facts and applicability

Floating offshore wind offers the potential for the offshore wind sector to become truly global. Approximately 70% of the world's population lives within 100 km of a coastline, and most of the global offshore wind resources occur in deep-water areas that are not accessible to fixed-bottom technology, which cannot be used in water depths over 100 meters. Because floating wind turbines can be deployed in waters more than 1,000 meters deep, they can bring the benefits of offshore wind power to many new areas and coastlines. Floating wind can also allow for offshore wind sites to be selected based on optimum wind speeds and conditions (areas further offshore tend to have stronger, steadier wind resources) rather than water depth.

Floating technology is rapidly evolving to be competitive with fixed-bottom solutions in transitional water depths—i.e., 50 to 100 m—where a fixed bottom solution such as a jacket-type structure could be used (see Figure 3-1). But the technology is still young, and to achieve cost-competitiveness with fixed-bottom options, floating technology needs to evolve further (see Section 5). The Gulf of Maine has significant areas with water depths of 50 to 100 m and vast areas with deeper water, all with some of the best wind resources in North America (see Figure 3-13). The conditions in the Gulf of Maine are ideal for advancing the development of floating wind technology in both transitional and deep waters.

Figure 3-1. Fixed-bottom and floating offshore wind foundations illustration, DHI/Wind Resources and Transmission Lines, NREL



3.2 Global market trends

The worldwide push for renewable energy sources is strengthening, driven by numerous private entity and governmental initiatives aimed at combatting climate change. According to the DNV ETO, wind power has been growing steadily since the early installations in the 1980s. Installed capacity reached 745 GW (5% of the global electricity output) in 2020. This power came mainly from onshore wind farms in Europe and North America. Five percent of the installed capacity is represented by offshore wind [1].

While Europe is currently leading the installed offshore wind capacity (see Figure 3-2), Asia and the United States are expected to assume a larger installed capacity share in the future [1]. While offshore wind in general can be considered significantly consolidated and a mature industry based on its 30 years of operational experience, the floating wind segment is still in the pre-commercial phase.

Currently, there are only three commercial floating wind farms in operation: Kindcardine (Scotland, 50 MW), Hywind (Scotland, 30 MW), and WindFloat Atlantic (Portugal, 25 MW) [38]. Any "commercial" deployment implies a TRL of approximately 9 (see Appendix B: Technology readiness level over the next decades). However, there are several floating wind farm commercial development initiatives worldwide, including Hywind Tampen (88 MW), which is under construction and is expected to be operating in Norway in 2022. The increasing attention being paid to the offshore wind industry, and particularly the industrialization and deep-water capacity from floating wind, is a positive sign of TRL improvement.

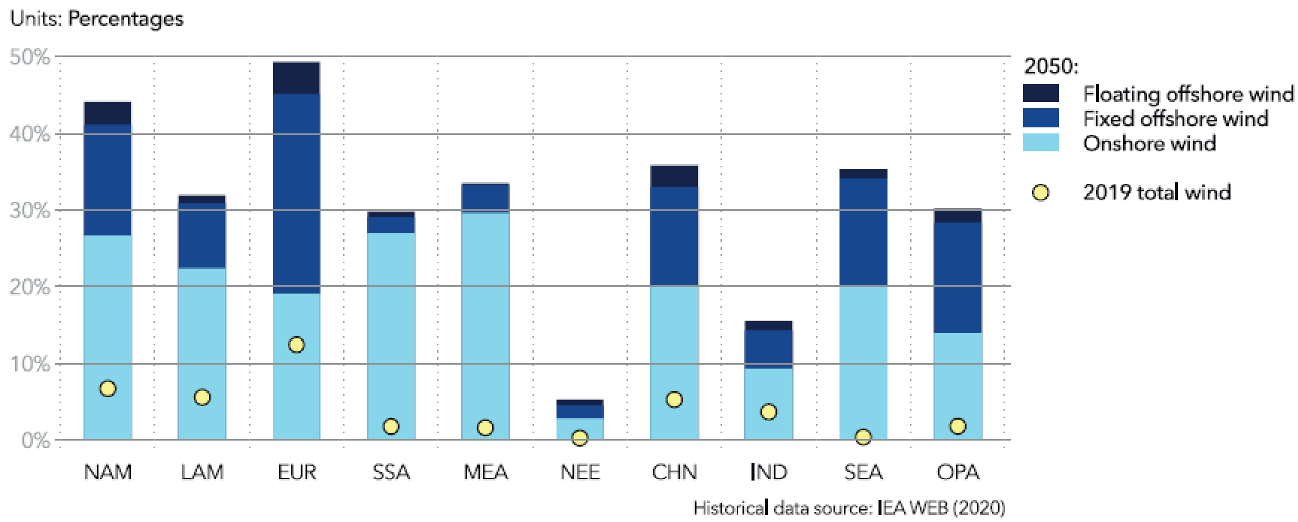
DNV's ETO model forecasts that onshore wind will face increasing resistance in developed countries with a mature industrial structure, and in areas with ongoing conflicts over turbine locations and/or lack of a stable policy and regulatory environment. Offshore wind, by contrast, is predicted to garner increasing support, especially in countries with limited available land area [1]. The increase in wind power, especially offshore wind, will be driven by financially supportive policies, infrastructure upgrades, increased environmental and climate awareness and regulatory stability and technology development and maturity [1].

3.2.1 Global offshore wind vs. onshore wind power relevance and capacity trend: electricity share generation by region

Globally, the electricity from wind power is projected to increase from 1.42 TWh/yr in 2019 to 17.84 TWh/yr in 2050 [1]. The increase in offshore wind power corresponds to a growth from 6% of the global wind electricity output in 2019 (745 GW) to 40% in 2050. About 15% of the offshore wind generation in 2050 is predicted to be generated by floating offshore wind [1]. There is currently 745 GW of installed capacity of wind energy worldwide and steady growth in this sector is forecasted over the next several decades; this includes the global trajectory for offshore wind, and specifically floating wind. Today, the offshore wind industry includes projects that make up only about 5% of total wind capacity worldwide (37 GW). However, upwards of 1,500 GW of fixed-bottom offshore wind and 250 GW of floating wind are expected to be installed by 2050. Figure 3-2 presents the share of wind electricity generation for each region, both status in 2019 for the total wind, and forecast for fixed and floating offshore, and onshore wind for 2050.

The development for offshore wind is linked to larger turbines and mega-sized projects combined with an evolving offshore supply chain. The cost drivers are further elaborated in Section 4.2. The ETO predicts a global total installed capacity of 260 to 270 GW for floating wind and 1,477 to 1,495 GW for offshore fixed wind by 2050.

Figure 3-2. Share of wind in electricity generation by region, status in 2019 and forecast for 2050 [1]



3.2.2 Offshore wind installation and forecast

Installed wind capacity for 2020 and forecasts from the DNV ETO for installed wind capacity in 2030 and 2050 are presented in Table 3-1. Globally, onshore, and offshore wind are predicted to increase steadily through 2050. Europe will continue to be the leading region for floating and fixed offshore wind, but it is predicted that Greater China will bypass Europe on floating wind by 2030 and be dominant in all wind power by 2050. The ETO predicts that North America will have a slow start but will reach the same level as Europe around 2050 [1].

Table 3-1. Installed wind capacity globally and forecast for 2030 and 2050 in GW [1]

Region	2020			2030			2050		
	Onshore	Fixed offshore	Floating offshore	Onshore	Fixed offshore	Floating offshore	Onshore	Fixed offshore	Floating offshore
World	709	35	0	1960	230	11	4150	1484	264

3.3 United States market trends

To estimate market trends for the US, DNV compared projections from the ETO [1] for North America with other industry projections, including the US Department of Energy (DOE)'s Offshore Wind Market Report: 2021 Edition [14] and Wood Mackenzie's US offshore wind market outlook 2021-2030. [7] Energy demand and policy drivers are also discussed as important contributors to the US market trend for the offshore wind industry.

3.3.1 Offshore wind installation and forecast

The ETO groups the data for the US and Canada together as the region "North America" (NAM). Table 3-2 presents the installed wind capacity for North America in 2020 and the expected installed capacity by 2030 and 2050 for onshore, fixed offshore, and floating offshore wind.

Table 3-2. Installed wind capacity for North America and forecast for 2030 and 2050 in GW [1]

Region	2020			2030			2050		
	Onshore	Fixed offshore	Floating offshore	Onshore	Fixed offshore	Floating offshore	Onshore	Fixed offshore	Floating offshore
NAM	136	0	0	389	26	1	573	232	47

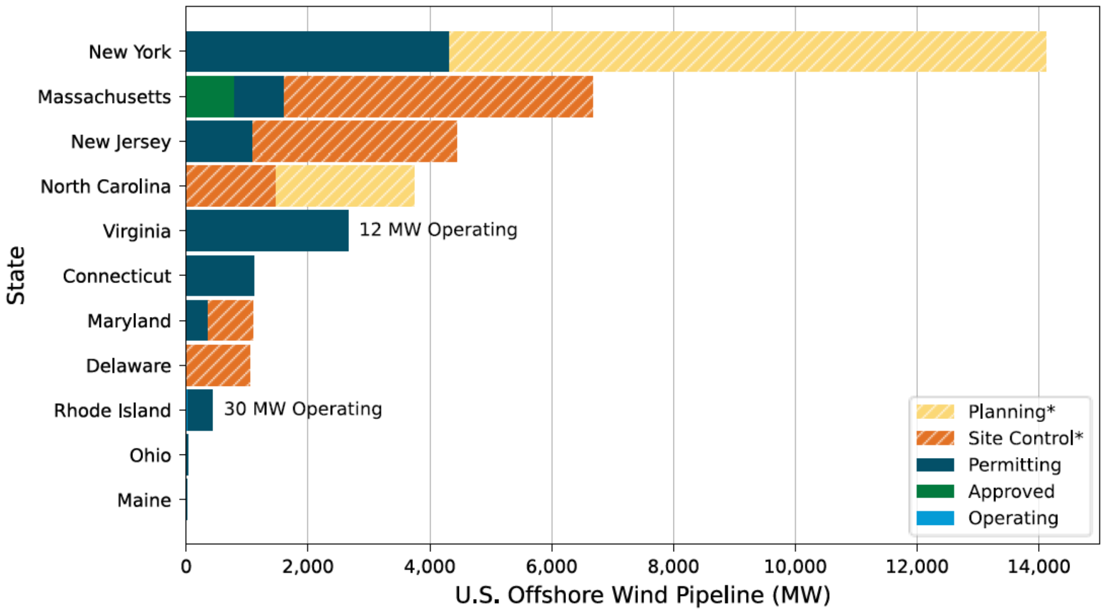
The Offshore Wind Market Report 2021 Edition [14] demonstrates the significant development activities and opportunities for offshore wind in US waters. Table 3-3 presents the current pipeline as of May 2021, divided into seven categories according to their status (or develop/operation stage) and certainty. The timeline stretches into uncertainty, as over 23 GW is still in either the site-control phase or is defined as unleased wind energy areas.

Table 3-3. Total US offshore wind pipeline [14]

Status	Description	Total [MW]
Operating	The project is fully operational with all wind turbines generating power to the grid.	42 MW
Under construction	All permitting processes are completed. Wind turbines, substructures, and cables are being installed. Onshore grid upgrades are underway.	0 MW
Financial close	Begins when the sponsor announces a financial investment decision and has signed contracts for major construction work packages.	0 MW
Approved	BOEM and other federal agencies have reviewed and approved a project's construction and operations plan (COP). The project has received all necessary state permits and has completed an interconnection agreement to inject power into the grid.	800 MW
Permitting	The developer has site control and has initiated permitting processes to construct the project and sell its power.	10,779 MW
Site control	The developer has acquired the rights to a lease area. Capacity is estimated using a wind turbine density of 3 MW/km2. Depending on market demand, developers may or may not incrementally build out projects to use a given lease area's entire size/potential.	11,652 MW
Unleased wind energy areas	The rights to lease areas have yet to be auctioned to developers by BOEM. Capacity is estimated using a 3 MW/km2 wind turbine density function.	12,051 MW
Total		35,324 MW

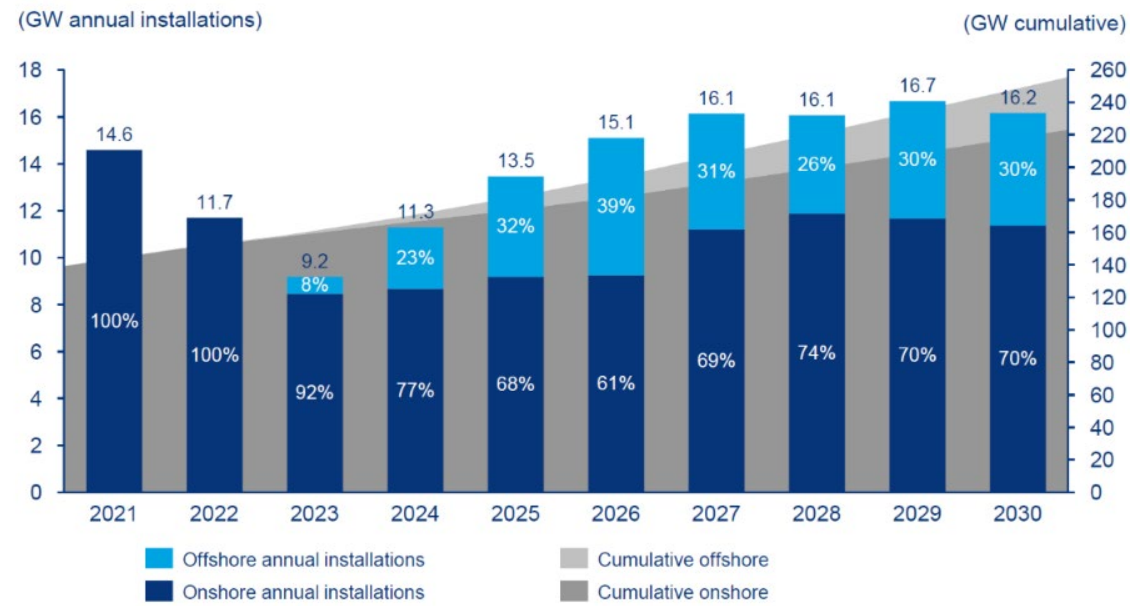
Figure 3-3 presents the pipeline of offshore wind projects by state indicating five out of the seven categories that were not zero in Table 3-3.

Figure 3-3. US project pipeline by state [14]



Wood Mackenzie presents an outlook for the US for both onshore and offshore wind from 2021 to 2030, shown in Figure 3-4. As seen in this figure, offshore wind in the US will not commence until 2023 but installations will steadily increase until 2026, at which time the installation rate is forecasted to flatten out. The increase in offshore wind will mainly be due to ambitious east coast states' renewable energy goals, with support from the federal government; this implies the need for clear and achievable deployment targets to sustain the necessary investments on infrastructure and transmission upgrades, the need for R&D investments to sustain the technology's LCOE reduction and the aforementioned investments on infrastructure upgrades. Offshore wind will be especially feasible for a state with a high proportion of the population close to shore, as capacity can be added in large swaths close to large load centers on the coast. [7] The US offshore wind market outlook 2021-2030 predicts that more than 72% of New York's wind capacity to be built will be offshore wind, and that in the Northeast region it will be close to 80%. [7] According to Wood Mackenzie (Figure 3-4), 32.5 GW of offshore wind will be installed in the US by 2030.

Figure 3-4. US onshore and offshore wind forecast for 2021-2030 [7]



Note: Cumulative figures are net, thus including decommissioning and repowering
Source: Wood Mackenzie

3.3.2 United States market energy drivers

The increasing demand for electricity and policies calling for clean energy are the primary drivers for developing offshore wind energy both globally and domestically. To enable the energy transition, political initiatives, infrastructure upgrades, and a stable and holistic regulatory environment are essential. These factors are needed to create the necessary boundary conditions – regulatory stability and growth prospects - to encourage the necessary level of investment for the development of the industry. Clear goals, visions, and investments in technology development, infrastructure, and supply chain will be necessary to achieve the climate objectives recently set by the Biden Administration.

3.3.2.1 Energy demand

DNV predicts an increase in electricity and hydrogen and a decrease in both total energy demand and oil and coal for North America towards 2050 (Figure 3-5). The main driver of the energy reduction is improvements to the transport sector (Figure 3-6). The energy demand for buildings will also be reduced, and this will mainly be due to energy efficient space heating (e.g., heat pumps), better insulation, and efficiency improvements.

Figure 3-5. Total energy demand per year for North America from 1980-2050 [1] historical and predicted data.

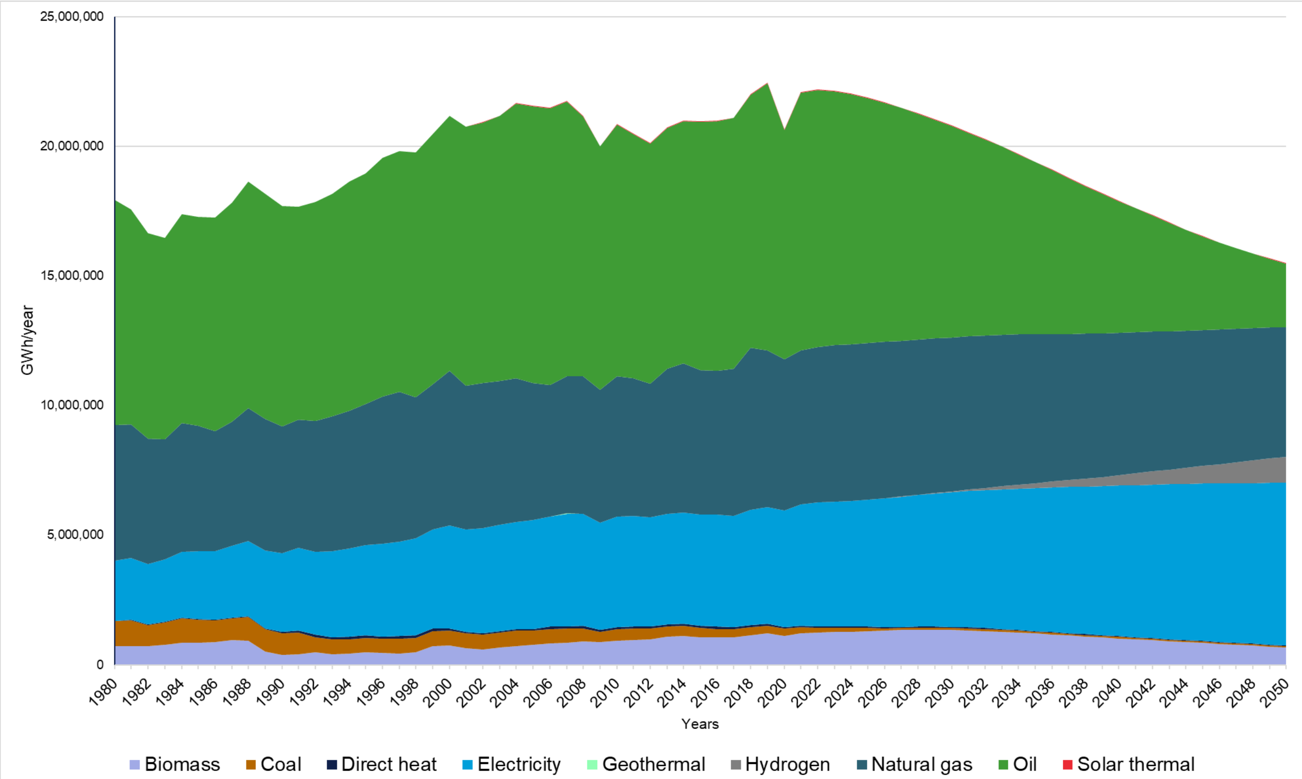
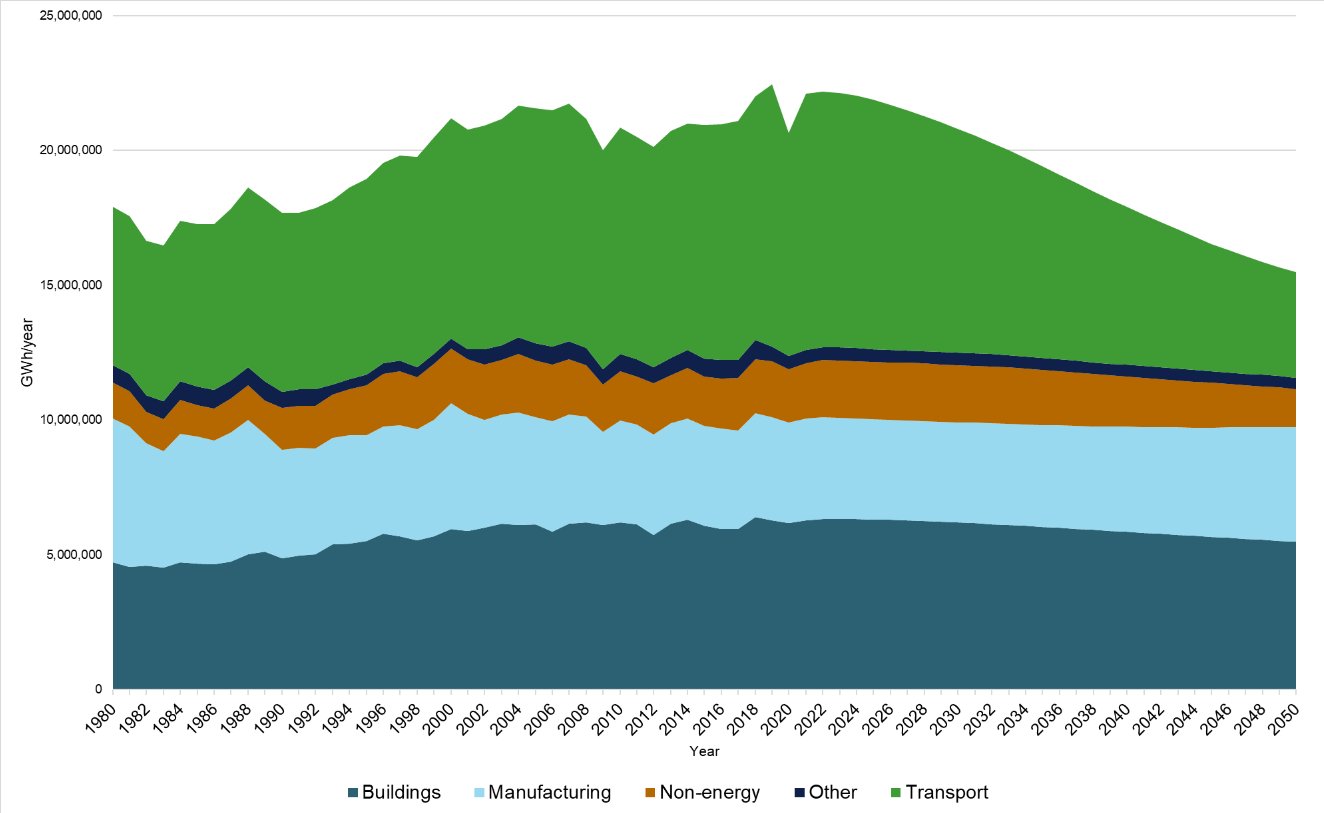


Figure 3-6 shows total energy demand for all North America forecasted to 2050. A drop is observed for 2020, corresponding to the decrease in energy demand caused by the COVID-19 pandemic. The energy demand is predicted to peak in North America around 2024. The flattening, and even reduction, in energy demand will be due to energy efficiency [1]. The efficiency gains are mainly related to electrification together with improvements in the transport sector, manufacturing, and buildings, in addition to advances in end uses such as insulation [1]. It is important to note that while overall demand is projected to decrease, the electrification demand within this window – both nationally and for Maine - is expected to increase, driven primarily by beneficial electrification in buildings and electric vehicles. DNV's expectations of electrification growth in Maine align with prior work conducted by the Maine Climate Council.

Figure 3-6. Total energy demand by sector per year for North America from 1980-2050, historical and predicted data [1]



Based on these projections, in North America the transport sector will experience the largest decrease in energy demand (a 30% decrease from the current level). The efficiency gain will mainly be related to the electrification of the passenger and commercial electric vehicle (EV) market segments, which will cut approximately 60% of transportation emissions [1].[1]

Figure 3-7 presents the predicted market share for the sale of electric vehicles (EV) for North America from 2019 to 2050. Converting to EVs will significantly decrease the demand for oil and increase the demand for electricity (Figure 3-8). For the electrification of the transport sector to be carbon neutral, the electricity must come from renewable energy sources [1].

[1] These projections do not assume policies recently proposed by the Biden Administration. It is anticipated that the effect of additional policies will be analyzed and included in future DNV ETO updates.

Figure 3-7. EV sales market shares outlook for 2019 to 2050 [1][2]

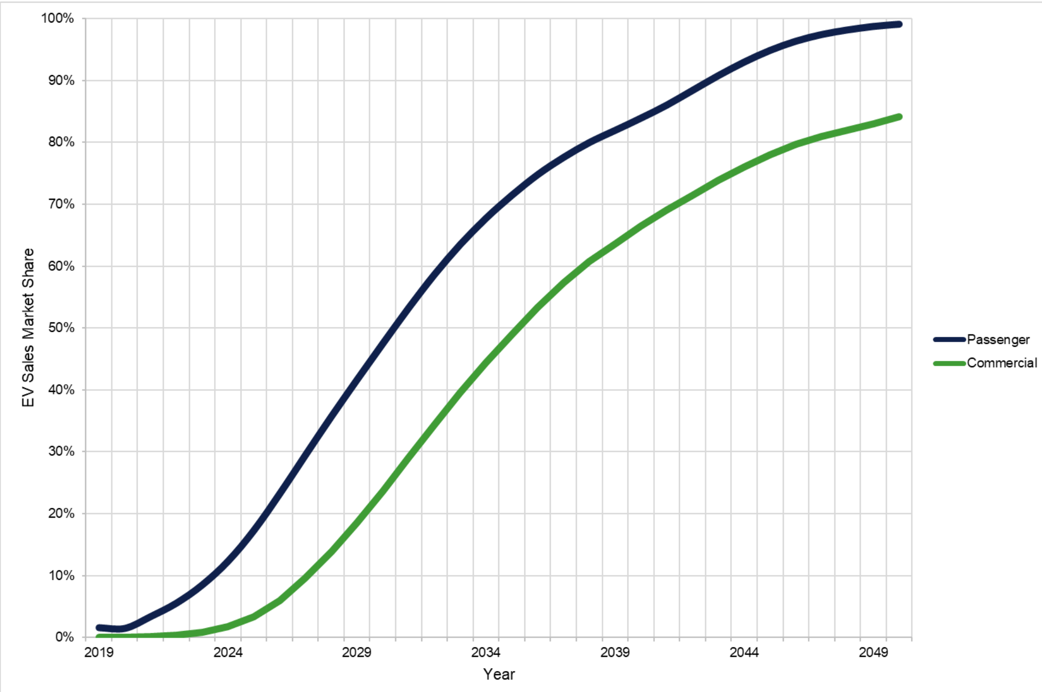
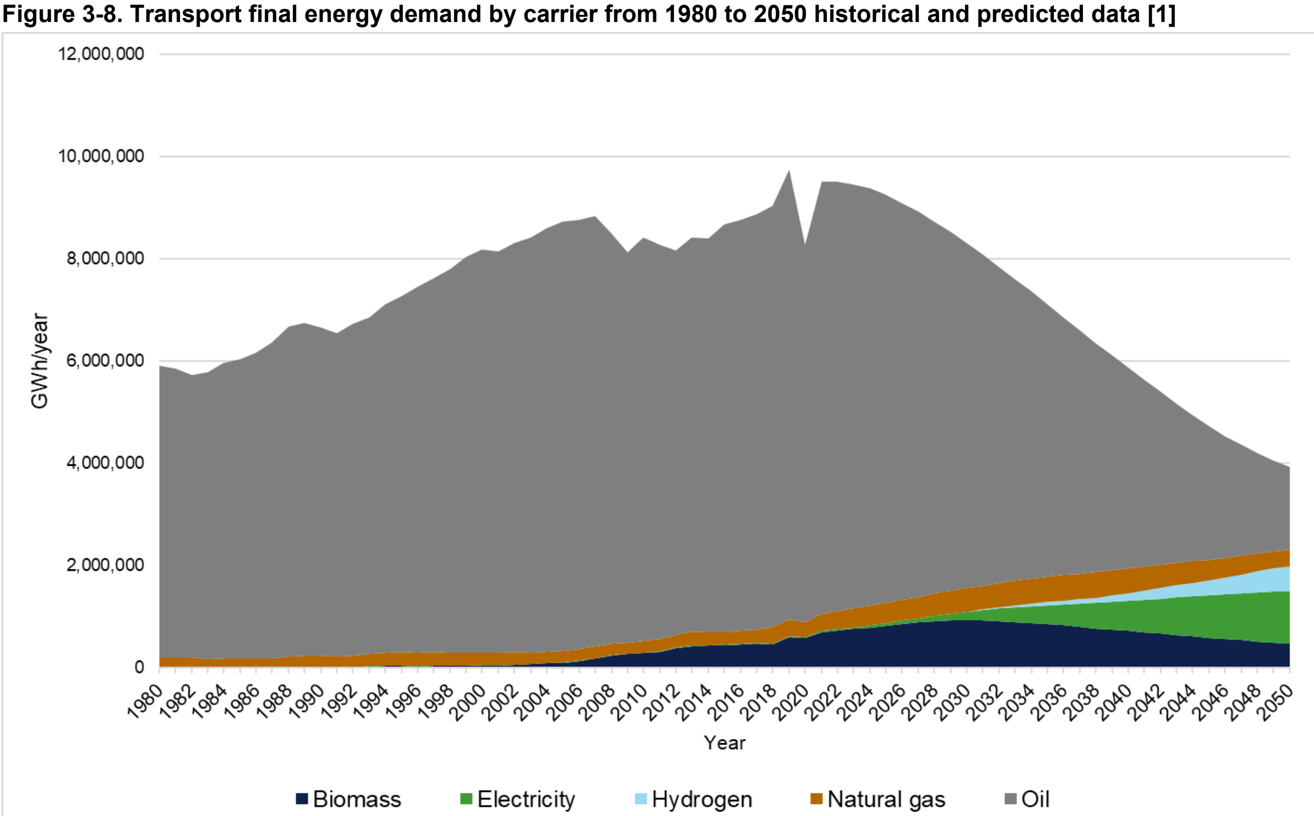


Figure 3-8. Transport final energy demand by carrier from 1980 to 2050 historical and predicted data [1]



[2] DNV's ETO model considers commercial to include light- and heavy-duty vehicle sizes.

3.3.2.2 Policy drivers

In 1992, the US Government, under President Clinton, adopted the Energy Policy Act (EPAct) to set goals, create mandates, establish tax credits, and amend utility laws to increase clean energy and improve overall energy efficiency. Its main objectives were to improve air quality and reduce dependency on foreign fossil fuels [85]. This EPAct has undergone numerous amendments since 1992. One of the most significant was under President Bush in 2005. This was the first US policy that identified specific commitments to use renewable energy, with a goal of 7.5% of total electric energy to be used by the federal government. Although offshore wind was not a feasible source at this time, implementation of the following was identified: solar, land-based wind, ocean (tidal, wave, current, or thermal), geothermal, municipal solid waste, or new hydroelectric generation [85]. Additionally, this amendment introduced three paths to achieving the renewable goal: installing on-site renewable energy, purchasing renewable energy, or purchasing Renewable Energy Certificates (RECs) [86].

Executive Order 13514 in 2009 by President Obama directed agencies to update building-performance standards and energy management practices through the use of Green Button Data and EPA Energy Star Portfolio Management. This order called for the management of consumption, promoted the reduction of GHG emissions, outlined achievable sustainability goals for the nation, and set a new goal for 20% of electric energy consumed to be sourced from renewable energy generation [86]. This executive order was amended in 2013 to create Federal Leadership in Environmental, Energy, and Economic Performance and the Interagency Climate Change Adaptation Task Force, led by the Council on Environmental Quality (CEQ), the Office of Science and Technology Policy (OSTP), and the National Oceanic and Atmospheric Administration (NOAA). It also gave federal programs specific sustainability goals and incentives to promote the utilization of clean energy, including offshore wind [86].

In 2017, President Trump withdrew from the Paris Agreement as part of his “America First” campaign. The Paris Agreement was viewed by the Administration as an unfair economic burden imposed on American workers, businesses, and taxpayers by US pledges made under the Agreement [89]. Additionally, as the prices of solar and wind technologies became less expensive, President Trump issued an order to incrementally reduce tax credits and similar incentives associated with renewable energy development (such as the lack of penalty for incidental avian take or death). Despite the repeal of numerous environmental or climate change-related incentives, President Trump did invest funds and create programs to support and promote renewable energy development in numerous rural areas. This was initiated in April 2017, by establishing the Interagency Task Force on Agriculture and Rural Prosperity to identify legislative, regulatory, and policy changes that could promote agriculture and prosperity in rural communities. In January 2018, Secretary Perdue presented the task force’s findings to President Trump. These findings included 31 recommendations to align the federal government with state, local, and tribal governments to take advantage of opportunities that exist in rural America [90]. Additionally, a focus was placed on reforming hydropower and exporting natural gas [91].

Emissions in the US were estimated to have declined 74% between 1970 and 2018, with the US net GHG emissions decreasing 13% between 2005 and 2017. Despite these reductions, further climate action was needed to combat the potential global climate crisis [88]. In January 2021, President Biden issued Executive Order 14008, which called for the Secretary of the Interior to identify steps to increase responsible renewable energy development on public lands and waters; this marked the nation’s first-ever wind goal to deploy 30 GW of offshore wind capacity by 2030, which would create an estimated 80,000 jobs [5]. The Biden Administration also set new climate targets including a carbon-free power sector by 2035 and a net-zero-emission economy by 2050 and has re-joined the Paris Agreement. These and other types of policy initiatives are driving how offshore wind energy is projected to grow, including its impact on the communities in which it develops and operates.

Build Back Better Agenda

In October 2021, President Biden announced the revised framework for America's Build Back Better Agenda [95]. This framework was originally released in March 2021 and requested 1.9 trillion USD to modernize the nation's infrastructure and combat the climate crisis. The American Rescue Plan was the first of the three-part agenda and was passed in March 2021, followed by the American Jobs Plan and the Infrastructure Bill. In August 2021, the US Senate passed a bipartisan 1.2 trillion USD Infrastructure Bill which called upon US Congress to invest in several major infrastructure areas: (1) roads, bridges, and major projects, (2) safety, (3) public transit, (4) passenger and freight rail, (5) EV infrastructure, (6) electric buses, (7) reconnecting communities, (8) airports, ports, and waterways, (9) resilience and western water infrastructure, (10) clean drinking water, (11) high-speed internet, (12) environmental remediation, and (13) power infrastructure [5]. In November 2021, the USD 1.2 trillion bipartisan Infrastructure Bill passed the US Senate, and although not finalized at the time of this reporting, represents the largest single investment into the clean energy economy in the history of the US. In late November, the House also passed the Build Back Better Act budget reconciliation bill that included USD 550 billion for climate and clean energy. As previously described, these funds are spread across buildings, transportation, industry, electricity, agriculture, and climate-smart practices across lands and waters. This framework sets the US on course to achieve a 50%-52% reduction in GHG emissions (below 2005 levels) by 2030, promotes environmental justice, and stimulates growth in domestic industries. More specifically, the Infrastructure Bill [96] and associated social policy measures promote private investment in and impact the demand for (and the effective supply of) offshore wind energy in the following ways:

- **Renewable Infrastructure:** Extend federal tax credits for offshore wind, other renewables and other low carbon technologies for 10 years along with direct pay among other provisions.
- **EV infrastructure**: Build out a national network of EV chargers with a focus on rural, disadvantaged, and hard-to-reach communities. President Biden has also set a target for EVs, hydrogen-fuel cells, and plug-in hybrid vehicles to make up 50% of new vehicle sales by 2030.
- **Electric buses**: Zero-emission buses, driving the demand for American-made batteries and vehicles, creating jobs, and supporting domestic manufacturing
- **Airports, ports, and waterways**: Port infrastructure to address repair and maintenance backlogs, reduce congestion and emissions near ports, and drive electrification and other low-carbon technologies
- **Environmental Justice:** Advance through a Clean Energy and Sustainability Accelerator that will invest in projects around the country and deliver 40% to disadvantaged communities
- **Environmental stewardship:** Bolster resilience and natural solutions to combating climate change through investment in forest management, soil conservation, and coastal restoration
- **Power infrastructure**: Upgrade power infrastructure, including the development of new, resilient transmission lines to facilitate the expansion of renewable energy. Also create a new Grid Deployment Authority, which invests in R&D for advanced transmission and electricity distribution technologies and promotes smart grid technologies that deliver flexibility and resilience. Invest in demonstration projects and research hubs for next-generation technologies, like clean hydrogen [5].

Jones Act

The Jones Act (46 U.S.C § 55102) is a coastwise trade statute from a section of the 1920 Merchant Marine Act. This law requires all cargo transported by water between two locations within American territory to be shipped on US-built, US-citizen-owned, and US-registered vessels (meaning crewed by Americans). As offshore wind is to be installed in American waters, the Jones Act will apply when using American ports. This protective law generates numerous American jobs and encourages a robust US Merchant Marine by having a large US-flag fleet [9]. It is also spurring the fabrication of special-purpose vessels needed to install US offshore wind farms.

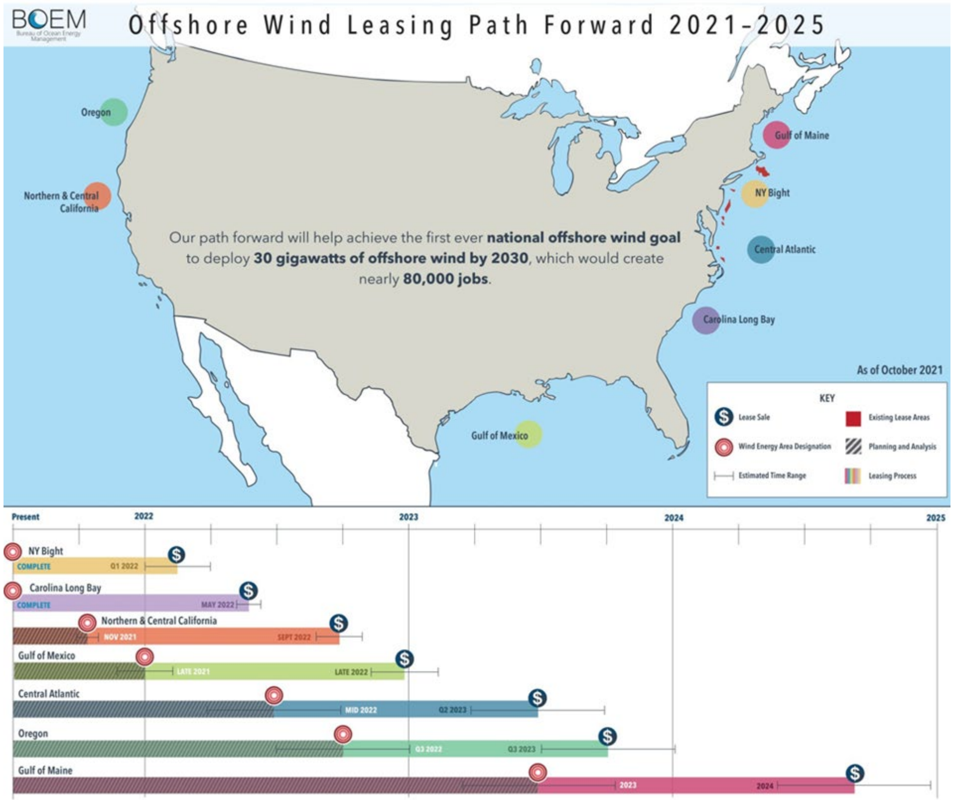
As of May 2021, two US-flagged wind turbine installation vessels (WTIV) have been announced. The GustoMSC vessel Charybdis is already under construction at Keppel AMFELS shipyard in Brownsville, Texas. Lloyd's Register and Northeast Technical Services Co., Inc. has announced plans for a vessel, but construction has not yet started [14]. The compliance requirement with this regulation, which is aimed at creating a minimum local content in the marine offshore operations space, will determine the need for an increased capacity provided by US-flagged vessels in most of the fixed offshore wind-related operations—in both installation and operation phases. Even when complete, however, these two Jones Act-compliant WTIVs will not be sufficient to meet the coming demand for installing fixed-bottom offshore wind turbines off the US East Coast. As a result, the industry has developed an alternative installation strategy to avoid project delays. The strategy is to use US-flagged feeder barges to ferry wind turbine components from US ports out to the project site where a WTIV from Europe or Asia may be stationed and available to complete the installations. Vineyard Wind will use this strategy, which is relevant for fixed-bottom installations only. For floating installations, a specialized WTIV is not required. The floating foundation structure is assembled at the construction port, the turbine assembly is then installed, and the entire floating assembly is towed by long-haul tugs from the port to the offshore site. Long-haul tugs are widely used in other offshore industries such as oil & gas and a Jones Act-compliant fleet exists.

Other specialized vessel types needed for offshore wind projects that are not widely available include cable-lay vessels (CLA) and service operation vessels (SOV). Non-US-flagged vessels may be used as long as they don't dock or resupply at a US port, but having Jones Act-compliant vessels would be preferable. As with WTIVs, the demand for CLAs and SOVs is likely to drive US shipyards to fabricate these vessels.

BOEM offshore wind leasing path forward 2021-2025

In October 2021, BOEM announced the timeline for the development of the main US offshore wind defined sites, including state-specific deadlines for Wind Energy Area Designations and Lease Sales (Figure 3-9). This important announcement is expected to create a tangible basis for state agencies, developers, port authorities, and other relevant industry players to design their planning strategies to sustain different offshore wind deployments in all these regions. Auctions for offshore wind leasing in the Gulf of Maine are expected to commence in mid-2024.

Figure 3-9. Offshore wind leasing path forward 2021-2025, BOEM



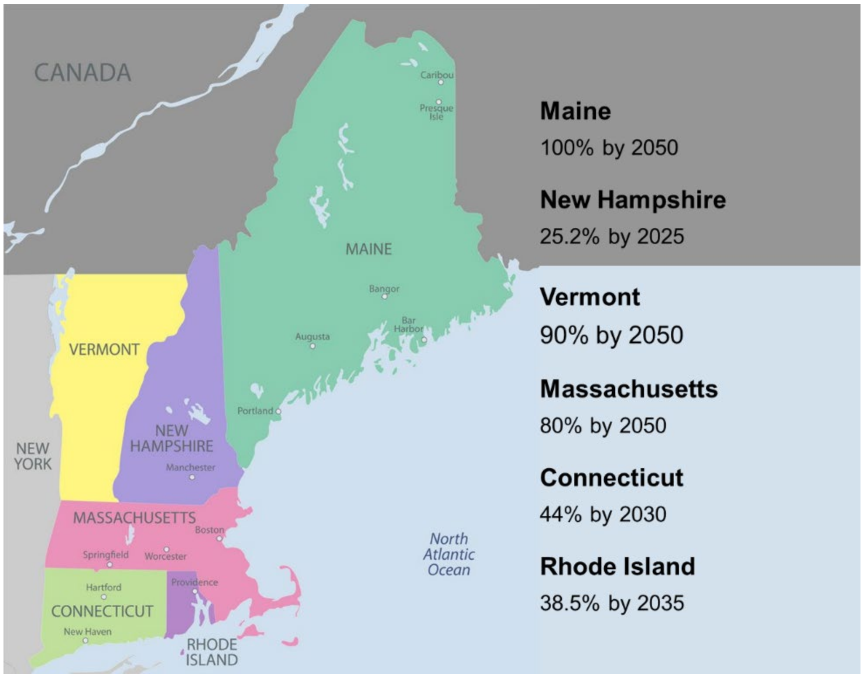
3.4 Regional market trends

This section highlights relevant market trends for the northeastern US and the individual states in the mid-Atlantic region with active offshore wind markets. It also assesses the state of the industry in Maine and describes the offshore wind potential in Maine.

3.4.1 New England

New England is expected to be a very active market for renewable energy deployment over the next decade. Each of the six states in the ISO has a mandatory renewable portfolio standard in place (Figure 3-10) and the region is increasing its dedication to offshore wind procurement, based on DNV research and data. As a result, there are estimates that over 12,500 MW of wind and solar capacity will be installed in the region by 2030 [1]. Throughout New England, approximately 6,900 MW of wind capacity is at various stages of development (see Table 3-4), primarily associated with large offshore wind projects [50].

Figure 3-10. New England States' Renewable Portfolio Standards (DNV, 2021)



In December 2016, the commercial operation of Rhode Island's Block Island Wind Farm marked a major milestone for the US offshore wind industry. Additional projects have positioned New England to deliver nearly 8 GW of utility-scale generation in the northeastern US by 2030. This anticipated growth of offshore wind capacity has led to a shift in focus toward understanding the potential impact of this technology on power system operations, rate payer electricity costs, and transmission infrastructure [51].

3.4.2 East Coast

Offshore wind is geographically positioned to consider transmission ties directly into major US coastal load centers, which could alleviate some already congested transmission paths. Potential points of offshore wind interconnection for ISO-NE and New York ISO are associated with existing points of interconnection above 345 kilovolts (kV). This interconnection and onshore infrastructure will be necessary as Connecticut, Massachusetts, and Rhode Island are currently installing fixed offshore facilities [60]. Table 3-4 details the Renewable Portfolio Standards for the New England States described above, and other players in the East.

Table 3-4. Renewable portfolio standards (RPS) and offshore wind target by 2030

States	RPS[40]		Offshore wind target by 2030 [MW] [6]
	%	Year	
Connecticut* **	44%	2030	2,000
Maryland	50%	2030	1,200
Massachusetts	80%	2050	4,000

States	RPS[40]		Offshore wind target by 2030 [MW] [6]
	%	Year	
Maine	100%	2050*	5,000
New Hampshire	25.2%	2025	-
New Jersey	100%	2050	3,500
New York	70%	2030	9,000**
Rhode Island* **	100%	2030	1,000
Vermont	75%	2032	-
Virginia	100%	2045/2050	5,200****

*State of Maine: 2030 requirement of 80% power generation from renewable sources
**New York State goal of 9,000 MW of offshore wind energy by 2035
*** 100% zero-carbon (CT) and renewable electricity (RI) goals established by Executive Order
****State of Virginia's goal of 5,200 MW has an established target of 2035

3.4.2.1 East Coast standards and goals by state

Connecticut

In late 2019, Connecticut's governor issued an executive order to re-establish and expand the responsibilities of the Governor's Council on Climate Change to address mitigation strategies to reduce greenhouse gases and consider adaptation and resilience in the face of climate change impacts [61]. This standard has three broad, fundamental objectives: zero-carbon electricity generation, clean transportation, and clean, efficient, and resilient buildings.

Currently, Connecticut has a 44% renewable target by 2030 and a 2,000 MW offshore wind procurement goal also by 2030 [61]. With 600 miles of coastline, Connecticut has been working to harness the offshore wind potential through a new offshore wind farm, Connecticut Revolution Wind. The Connecticut portion of this project is located approximately 50 miles from New London, in federal waters. The State is hopeful that approval of this 200 MW wind farm will not only fuel progress toward the renewable target and future wind development, but also provide positive economic impacts to the port of New London [62].

Maryland

Offshore wind projects are being pursued within Maryland to help reduce greenhouse gas emissions while creating positive economic impacts, including revitalization of sectors of Maryland's economy such as manufacturing, maritime, and port logistics industries and creation of thousands of high-paying jobs [63].

In support of offshore wind development, the State passed the Maryland Offshore Wind Energy Act of 2013. This initiative revised the RPS goal to source 25% of all electricity consumed in the State from renewable energy by the year 2020. In November 2016, the Maryland Public Service Commission (PSC) began reviewing two proposed projects submitted by Skipjack Offshore Energy, LLC and U.S. Wind, Inc. which total 368 MW. In May 2017, the PSC announced in Order No. 88192 that both projects were approved, with conditions [63].

In 2019, the standard was again revised through the Clean Energy Jobs Act. This increased Maryland's overall RPS to 50% by 2030 and requires the procurement of at least 1,200 MW of offshore wind capacity [63]. In July 2021, the State began reviewing five proposed projects submitted by Skipjack Offshore Energy, LLC, and U.S. Wind, Inc. Project review is anticipated to be completed by December 2021 [63]. Skipjack, if approved, will be the first US proposed subsea transmission system capable of delivering 120 MW to the State of Maryland.

Massachusetts

In 2018, in response to the Global Warming Solutions Act (GWSA), which stipulated greenhouse gas emissions reductions for the Commonwealth, the Department of Environmental Protection of Massachusetts established the Clean Energy Standard, setting a minimum percentage of electricity sales that utilities and competitive retail suppliers must procure from clean energy sources [64]. The minimum percentage began at 16% in 2018 and increases 2% annually to 80% in 2050 [60].

Massachusetts has one of the most complex packages of renewable energy statutes in the country. The State has in place a clean energy standard, a clean peak energy standard, an alternative energy portfolio standard, a solar carve-out, and an offshore wind procurement goal. In August 2016, Governor Baker signed an act to allow for the procurement of up to 1,600 MW of offshore wind energy by 2027, and in March 2021 signed an *Act Creating a Next Generation Roadmap for Massachusetts Climate Policy* which increased offshore wind procurement goals to 4,000 MW [66]. Massachusetts also increased their RPS to 40% by 2030 and economy-wide emission reduction targets to 50% below 1990 levels by 2030, 75% by 2040 and net-zero emissions by 2050. On June 29, 2017, the Massachusetts Electric Distribution Companies, in coordination with the Massachusetts Department of Energy Resources, sought long-term contracts for offshore wind energy projects and announced the selection of Vineyard Wind, estimated to harness 800 MW of offshore wind energy [65].

New Hampshire

The Renewable Energy Fund was created in 2007 as a component of legislation known as the Renewable Portfolio Standard. It mandates that 25.2% of the State of New Hampshire’s electricity comes from renewable sources by 2025 [60] [68]. Three main sources of renewable energy generation include solar electric, solar thermal, and wind. In December 2019, Governor Sununu issued an offshore wind executive order with obligations. New Hampshire is preparing for offshore wind development in the Gulf of Maine and will continue to engage with BOEM and the neighboring states [67].

New Hampshire is one of three states, along with Massachusetts and Maine, participating in the BOEM Gulf of Maine Renewable Energy Task Force. This Task Force, comprising local and state elected officials and agency representatives, is recognized federally as the first step towards development [67]. During meetings, members discuss and finalize lease areas in federal waters off the New England coast, along with various other important topics related to offshore wind development including impacts on wildlife, fishing, ocean travel, and more.

In 2019, New Hampshire was anticipating six to ten years before an approved offshore facility would be under construction. It is estimated that the coast of New Hampshire has sufficient offshore wind potential to supply 2,600 MW, enough to power the entire state [67]. Recognizing this potential, pending Senate Bill 151 calls for 800 MW of renewable energy by June 30, 2028, with 600 MW of the renewable energy solicitations coming from offshore wind energy [69].

New Jersey

In May 2018, the New Jersey Governor Murphy’s Executive Order directed the New Jersey Board of Public Utilities, in partnership with other state agencies, to develop a statewide clean energy plan and shift away from energy production that contributes to climate change [70]. In January 2020, Governor Murphy unveiled New Jersey’s Energy Master Plan, which addresses New Jersey’s energy system, including electricity generation, transportation, and buildings, and their associated greenhouse gas emissions while outlining key strategies to reach the Administration’s goal of 100% clean energy by 2050. The Plan outlines the seven key strategies, including Strategy 2 to accelerate the deployment of renewable energy and distributed energy resources through the development of offshore wind, community solar, and energy storage. Other key action areas include reducing energy consumption, expanding clean energy jobs, and encouraging the use of increased numbers of EVs.

The New Jersey Board of Public Utilities (NJBPU) serves as the lead Energy Master Plan Committee and is organized into the following five work groups: clean and renewable energy, sustainable and resilient infrastructure, reducing energy consumption, clean and reliable transportation, and building a modern grid [70].

In addition to two offshore wind farms proposed, Garden State Offshore Energy and Ocean Wind, there are numerous BOEM lease areas in the vicinity of New Jersey. Garden State Offshore Energy is proposed to be located approximately 20 miles off the coast of New Jersey, to produce 1 GW of clean energy, and consists of nearly 200 turbines [70]. Ocean Wind is a proposed 1,100 MW facility located approximately 15 miles off the coast. This project will utilize the GE Haliade-X 12 MW turbine, which is the most powerful turbine on the market today [71]. In addition to progressing these significant wind facilities, a recent study conducted by the US Coast Guard indicated that New Jersey intends to develop the first purpose-built wind port on the East Coast. This port will have no vertical restrictions, easy access to more than 50% of the available US offshore wind lease areas, and a location on the eastern shore of the Delaware River in Salem County [72].

New York

In 2019, the historic Climate Leadership and Community Protection Act was signed into law, known as the Clean Energy Standard. This standard requires New York State to achieve a 100% carbon-free electricity system by 2040 and to reduce greenhouse gas emissions 85% below 1990 levels by 2050. This aggressive policy set a new standard across the US to expedite the transition to a clean energy economy [73]. This law mandates that 70% of electricity within the State shall come from a renewable energy source by 2030. This plan also calls for the development of 9,000 MW of offshore wind energy by 2035 [73]. According to numerous sources, New York is well on the way to developing 9,000 MW of offshore wind energy through the State’s second solicitation for offshore wind. New York State Energy Research and Development (NYSERDA) has provisionally awarded two projects, Empire Wind 2 and Beacon Wind of Equinor Wind U.S. LLC, bringing the State’s total to five projects of over 4,300 MW in active development. Additional projects proposed within New York offshore lease areas include Sunrise Wind, an 800 MW facility, and Southfork Wind, a 130 MW facility [74]. Onshore and offshore construction is planned to begin in 2022.

Rhode Island

In 2004, Rhode Island General Assembly enacted a Renewable Energy Standard. This initial standard was set to achieve 16% renewable energy by 2019 and was updated in 2016 to achieve 38.5% renewable energy by 2035. Governor Raimondo established aggressive goals regarding climate change, including advancing 100% renewable electricity by 2030 [60] and increasing in-state renewable energy tenfold by 2020 (to 1,000 MW) through new development and regional procurement [75]. The governor’s executive order directed the State's Office of Energy Resources to conduct an economic and energy market analysis and develop actionable policies and programs the state could pursue to reach this goal.

In support of these aggressive goals, the State has not only approved substantial utility-scale solar projects but was the first state in the country to construct an offshore wind farm. Block Island Wind Farm produces approximately 30 MW of renewable energy. A second wind facility, Revolution Wind Farm, set to become operational by 2023, is proposed approximately 15 miles off the coast of Rhode Island with 50 turbines generating 400 MW of renewable energy [62].

Vermont

Vermont’s Renewable Energy Standard established requirements for electric distribution utilities. This standard began at 55% in 2017 and increases by 4% every three years, eventually reaching 75% in 2032 [76]. Vermont plans to reach this goal primarily through contracted hydroelectric generation [60].

In 2016, the Comprehensive Energy Plan further defined the path to 100% electricity generation from renewable resources. Despite having no access to the offshore wind resources that neighboring New England states possess, Vermont, by 2020, generated almost 100% of its electricity from renewable resources, a larger share than any other state. About 58% of Vermont's utility-scale in-state generation came from conventional hydroelectric power while five utility-scale wind farms accounted for about 15% of the State's total electricity net generation [77].

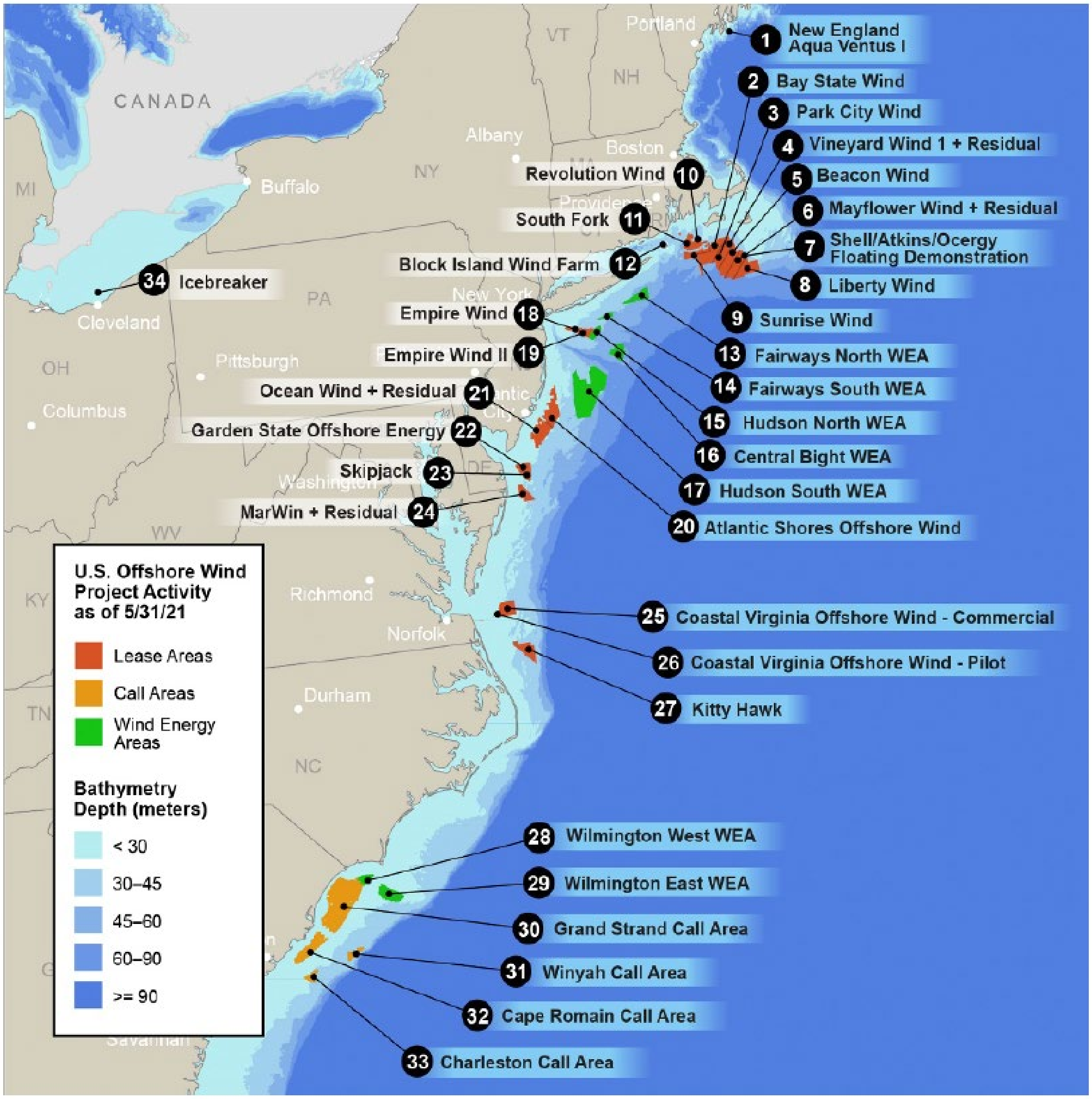
The projects described through the New England states, current lease areas, wind energy areas, call areas and approximate water depths along the east coast of the US are depicted in Figure 3-11.

Virginia

In 2007, the General Assembly for the Commonwealth of Virginia passed legislation establishing incentives for the implementation of a renewable energy portfolio standard program [82]. In April 2020, Virginia Governor Northam increased portfolio standard requirements and targeted Phase I and Phase II utilities to generate 100% of their power from renewable sources by 2050 and 2045, respectively. Renewable energy sources defined under this legislature include wind, solar, biomass, hydro, energy from waste, landfill gas, municipal solid waste, geothermal power, and wave motion. Further, utilities are required to procure specific amounts of power generation from solar and onshore wind sources by a specific date [84]. In 2020, Governor Northam signed landmark offshore wind legislation that established a target for Virginia to generate 5,200 MW of offshore wind energy by 2034, providing a path for the development of at least two offshore wind projects that are currently planned to interconnect into Virginia [82].

The State Corporation Commission (SCC) approved the Coastal Virginia Offshore Wind (CVOW) demonstration project in August of 2018 as the first in the State as well as the first utility-owned offshore wind farm in the US. Dominion Energy partnered with Ørsted to construct the two 6 MW wind turbine projects, located approximately 27 miles off the coast of Virginia Beach. This project is located within acreage leased by the Virginia Department of Mines, Minerals and Energy (DMME). DMME has the only research lease for offshore renewable energy awarded by BOEM [93]. In June 2021, Governor Northam announced the State would be the first in the US to utilize the new federal permitting initiative, accelerating offshore wind development. Dominion Energy submitted plans to construct a 2.6 GW project to the SCC for approval in November 2021. When fully constructed in 2026, the CVOW project is anticipated to deliver up to 8.8 million MWh per year of clean, renewable energy to the grid, powering up to 660,000 Virginia homes [94].

Figure 3-11. Location of US East Coast wind pipeline activities and call areas as of May 31, 2021 [14]



3.4.2.2 Regional Greenhouse Gas Initiative

The Regional Greenhouse Gas Initiative (RGGI) is the nation's first multi-state program to reduce power sector CO_2 emissions. The RGGI states establish a regional cap on CO_2 emissions that power plants can emit by issuing a limited number of tradable CO_2 allowances. Each allowance represents an authorization for a regulated power plant to emit one short ton of CO_2, and each CO2 budget trading program in each RGGI state together create a regional market for CO_2 allowances to be bought and sold

Proceeds from the RGGI drive significant investment in energy programs in participating Eastern states, including Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia. The programs funded in 2019 accounted for USD 217 million in RGGI investments and were estimated to return USD 1.3 billion in lifetime energy bill savings to over 26,000 households and over 1,400 businesses that participated in programs funded by RGGI proceeds, while over 130,000 households and businesses received direct bill assistance. States have individual discretion over how RGGI proceeds are invested; however, investments fall into four major categories, including:

1. Energy efficiency (40% of 2019 RGGI investments),
2. Clean and renewable energy (15% of 2019 RGGI investments),
3. Greenhouse gas abatement (15% of 2019 RGGI investments), and
4. Direct bill assistance (19% of 2019 RGGI investments) [83].

As a contributor to carbon-free electricity and a participating state in the RGGI, Maine can leverage its position as a market leader in renewable energy. More specifically within offshore wind, Maine could support other participating states with a reduction in the region's CO_2 emissions while utilizing RGGI investments to offset, for example, the impact of offshore wind on ratepayers through direct bill assistance programs and continued energy efficiency improvements.

3.4.3 Maine

This section identifies trends and opportunities for Maine to support and develop the offshore wind industry. This includes a discussion of the key policy drivers within the state, as well as the potential for offshore wind and implications for both fixed and floating turbine development.

3.4.3.1 Policy context

In 2010, the Ocean Energy Act was signed into law in effort to establish a new renewable energy industry within the Gulf of Maine. This Act outlined and recommended regulatory improvements between agencies that would facilitate development of renewable facilities across the State [97].

Although many initiatives and program revisions were accomplished through the Ocean Energy Act, recent changes in energy demands, as well as available technologies that support renewable development, paved the way for the State of Maine to strive for greater and more specific renewable energy commitments. In the Spring of 2019, the Maine Legislature enacted L.D. 1464 – An Act to Support Electrification of Certain Technologies for the Benefit of Maine Consumers, Utility Systems, and the Environment. In alignment with GHG emissions reduction goals, this bill required Efficiency Maine Trust to study the barriers and opportunities for beneficial electrification and driving deep decarbonization. The deep levels of decarbonization through the electrification of fossil fueled based systems will result in increased electricity demand, not only based on changes in population, but also due to beneficial electrification of heating and transportation systems.

Along with the Beneficial Electrification Bill, Governor Mills signed three other policies (LD 1679, LD 1494, LD 1711) into legislation in 2019 to reform Maine's Renewable Portfolio Standard requiring 80% of Maine's electricity to come from renewable resources by 2030, with a goal of 100% by 2050 [55]. These policies promote clean energy jobs and the development of clean energy projects. The Maine Climate Council, also established under these policies, has been tasked with developing pathways to reach economy-wide carbon neutrality while the Public Utilities Commission must procure long-term contracts for new clean energy generation, which may be paired with advanced energy storage, and requires renewable energy policy studies to be conducted in conjunction with other planning efforts [55]. These policies were developed to ensure an adequate and reliable supply of electricity for Maine residents and to encourage the use of renewable, and local, resources and diversify renewable electricity production. With these goals, Maine has implemented one of the most ambitious renewable energy programs in the country, and consequently, anticipates a revamp of the electric sector to support rapid load growth.

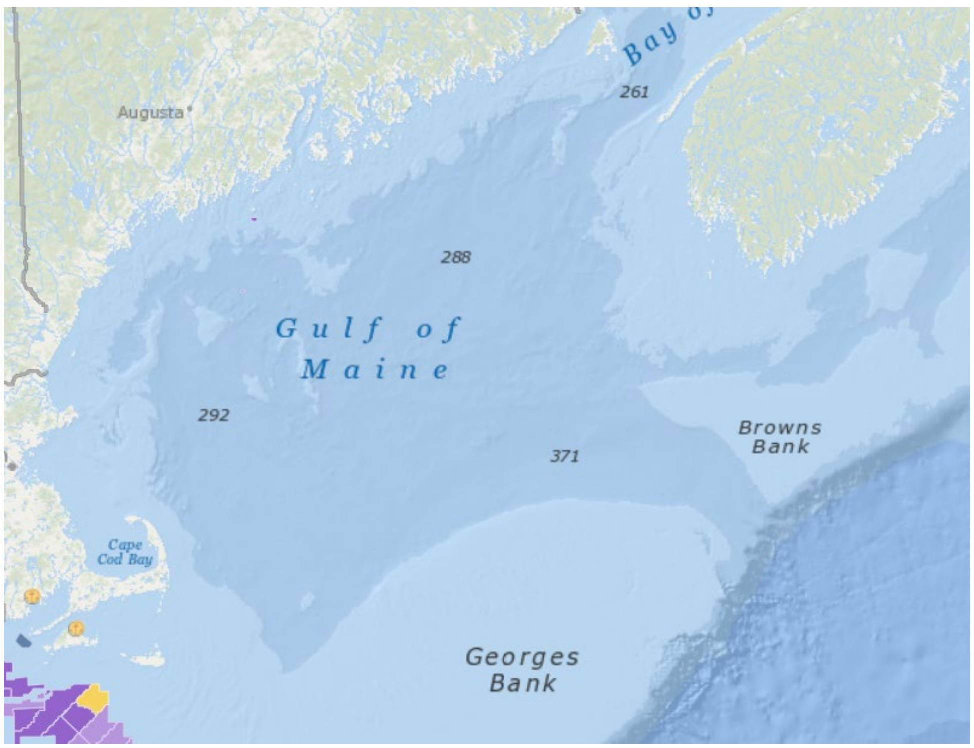
The Governor's Energy Office identified offshore wind as a primary component for meeting Maine's renewable energy targets and addressing climate change [56]. Although Maine has very high-quality offshore wind potential, it is largely inaccessible, and significant transmission and distribution upgrades are likely needed to interconnect large amounts of offshore wind energy into both Maine's existing infrastructure as well as the infrastructure throughout the Gulf of Maine regionally.

Further, and beyond benefits to the state of Maine specifically, Maine is hopeful about the prospect of contributing to the ability of the greater New England region to achieve its renewable energy goals and meet high energy demands. Maine offers ample opportunity to contribute its maritime experience, innovative research, including floating offshore wind, and high-quality wind resources to support and grow the responsible development of an offshore wind industry in the US.

3.4.3.2 Maine's offshore wind potential

The Gulf of Maine is an area of approximately 36,000 square miles (sq. mi.) and contains several dramatic underwater features reaching depths of roughly 1,200 ft. The Office of Coast Survey nautical charts identify Maine State Waters out to 3 nm and the extent of US federal waters from 24 nm to 200 nm [17]. As seen in Figure 3-12, the water depth in the continental platform and Gulf of Maine waters ranges up to 300 meters (m), 985 feet (ft).

Figure 3-12. Overview of the Gulf of Maine with potential wind developable area [8]



Offshore wind energy offers Maine the potential for long-term job creation and economic development, a greater degree of energy independence, supply chain and port infrastructure investments, and renewable power to help meet the State's ambitious clean energy and climate change goals for renewable development of 3,000 MW by 2020 and 8,000 MW by 2030. The State further identified 300 of the 3,000 MW (by 2020) and 5,000 of the 8,000 MW (by 2030) should be generated from renewable facilities located in coastal waters [56] [99]. Although the 2020 goal for offshore wind installation has not been met, the State of Maine has committed to the 10-year Economic Development Strategy, with a Roadmap to be completed by December 2022, in which offshore wind is highlighted as a key opportunity for the State to meet these energy goals [26].

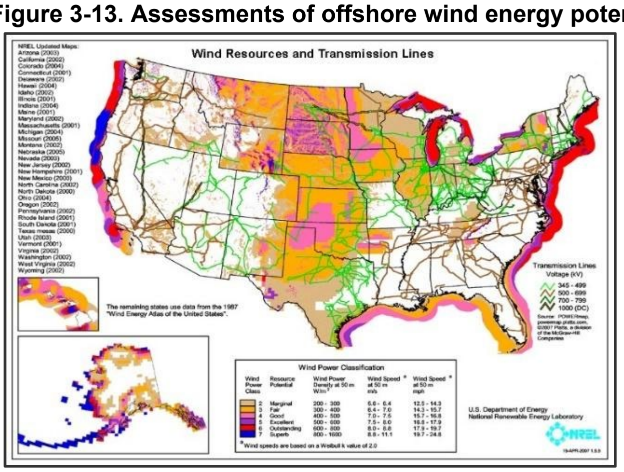
Additionally, the floating offshore wind research array is assumed to produce approximately 144 MW in 2025 [55], making floating wind a potential source of renewable energy.

Through the Maine Offshore Wind Initiative, launched in June 2019 by Governor Janet Mills, the State is exploring opportunities for the thoughtful development of offshore wind energy in the Gulf of Maine and determining how to best position Maine to benefit from an industry expected to generate $1 trillion in global investment by 2040. This Initiative is aligning itself with nationwide momentum and offshore wind market maturity that has developed during the last decade to make offshore wind a more competitive renewable energy option. The Initiative aims to balance this industry's development with the State's maritime heritage and existing marine uses to ensure sustainable preservation of the natural resources in the Gulf of Maine [56].

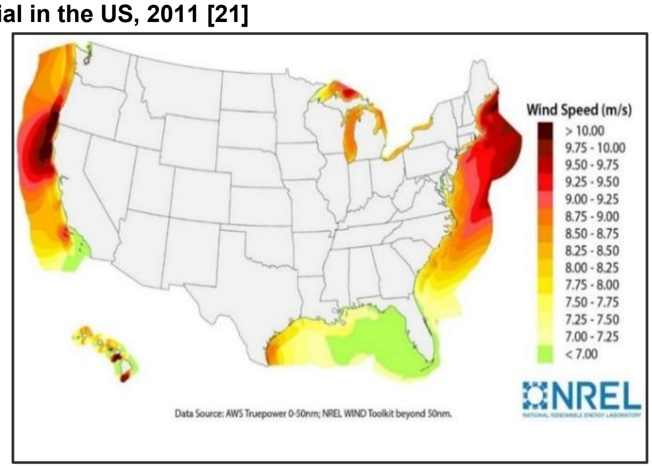
Consideration of the long-term benefits of offshore wind can enable Maine to exceed and maintain the renewable energy goal of 100% by 2050 through use of vast shorelines and harnessing some of the greatest offshore wind energy potential within North America [18] [19]. Offshore wind could provide a source of electrical generation incrementally that other renewable resources may not be able to provide, including spatial development constraints and electricity storage costs. Figure 3-13 and Figure 3-14 show the estimated offshore wind potential for Maine in comparison to the US as well as the neighbouring states bordering the northern Atlantic Ocean. Both figures use a color scale; the darker colors represent the areas with the greatest wind resources or speeds, thus, identifying areas with the greatest developability for offshore wind facilities. More specifically, Figure 3-13(b) identifies areas of lowest wind energy generating potential in yellow, with areas of increasing potential to reds and greatest to blue. Figure 3-13(a) also outlines the major transmission lines, by voltage, for distributing energy. Lower capacity lines are light green while the high-capacity lines are dark brown. Figure 3-13(b) uses green and yellow to represent areas of lowest wind speeds and dark oranges and reds to identify areas of greatest wind speeds. Both the scale and estimated wind speeds are consistent in these figures as applicable to Maine.

Figure 3-14 provides a closer look at the north-eastern US and shows the potential off the coast of Maine in higher resolution. Note that any area with mean wind speeds greater than 9.0 m/s is considered excellent, and nearly the entire Gulf of Maine falls into that category.

Figure 3-13. Assessments of offshore wind energy potential in the US, 2011 [21]

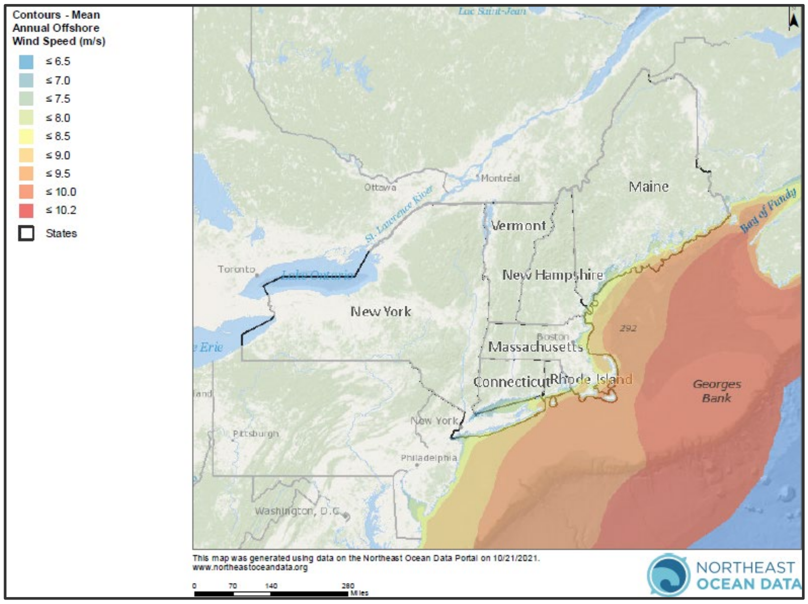


(a) Wind resources and existing transmission infrastructure in the US, including Alaska



(b) Wind resources in US, displays high wind resource potential along the coast of Maine

Figure 3-14. Offshore wind energy potential, coast of Maine, 2021 [20]



The offshore wind energy potential in Maine has the estimated capacity to supply 913% of the State's electrical generation, which is greater than any other state bordering the Atlantic [19]. Maine ranked seventh in the US with more than 411 TWh/yr of offshore resource generating potential, which could benefit not only the State of Maine but also local and global regions [22]. Table 3-5 details the quantity of offshore wind resource potential in Maine in state versus federal waters. This table is based on an analysis performed by the National Renewable Energy Laboratory (NREL) on behalf of the US DOE [22].

Table 3-5. NREL offshore wind resource potential in the State of Maine, 2018 [22]

Ocean area with minimum average wind speeds of 7 m/s	
State waters	17,990 km^2
Federal waters	108,304 km^2
Total	**126,294 km^2**

This energy can be harnessed using both fixed and floating offshore wind turbines and with consideration to the implementation of emerging technologies.

Fixed offshore wind development

Maine has water depth ranges that make it infeasible to install fixed offshore wind farms throughout most of its offshore acreage, as described in Section 3.1. However, Maine can support the growth of the fixed offshore wind industry throughout New England by making potential infrastructure upgrades, developing an offshore wind supply chain, and making specialized workforce development improvements for a floating wind industry available to the wider offshore wind industry segment.

Maine can support work performed in the Atlantic through the use of the current Maine port-based infrastructure, supply chain companies, and workforce, many of which have expertise in oceanic-related fields including transportation and vessel navigation [23] [24]. Further, through the use of the existing manufacturing and construction industries within the State, Maine could supply materials to neighboring states, such as New York, Massachusetts, and Rhode Island, which currently have numerous fixed offshore wind farms proposed along their coastlines.

Floating offshore wind development

The State of Maine is pursuing federal approval for the Gulf of Maine Floating Offshore Wind Research Array, a 16-square-mile area in federal waters off the Gulf of Maine. The array will feature up to 12 turbines on innovative floating platform technology developed by the University of Maine and is the prudent next step in Maine's advancement of floating offshore wind [56]. Given the characteristics and depth of the ocean floor, offshore wind development activity in Maine in the near term is best served by the new floating technologies being proposed [20].

Maine's existing maritime heritage and workforce can support both the onshore assembly of floating wind foundations (platforms and substructures) and the transport of the constructed structures to installation locations via Maine barges and vessels Therefore, floating offshore wind foundations can be fabricated and/or assembled locally and will not require the development of new shipyards or vessels specifically designed to assemble and install offshore wind structures onsite [24]. Land-based construction in Maine could promote the installation of floating offshore wind farms to begin in the US by eliminating the need to use the type of much larger, more expensive, and highly specialized foreign vessels that are required for fixed-turbine installation. These vessels are currently unavailable in the US (Jones Act, Section 3.3.2.2).

4 COST TREND PROJECTIONS

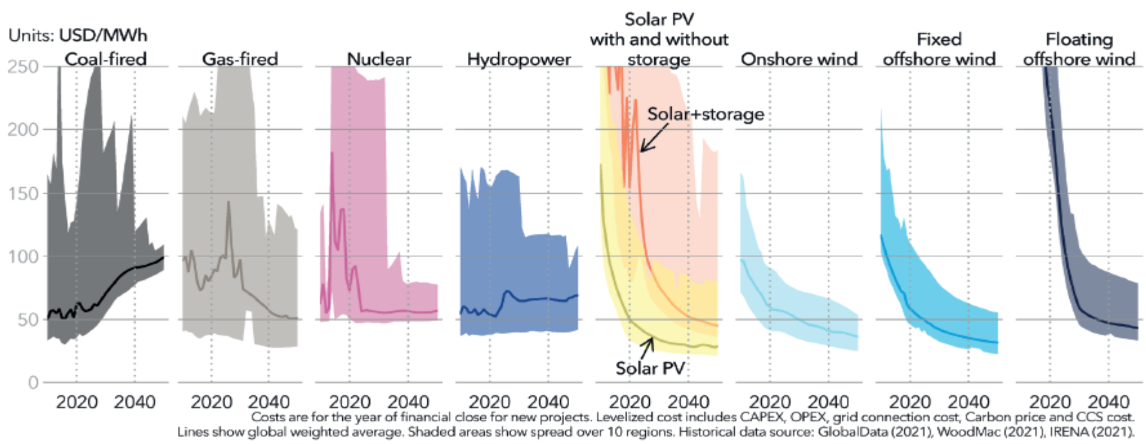
4.1 Cost trends for deep-water offshore wind and available technologies

4.1.1 Global energy market

The cost trend projections for the LCOE for several different power station types are presented in Figure 4-1. The metric used to quantify the cost and its trends for all these energy sources is the LCOE, which measures the cost of energy for producing a megawatt-hour of electricity over the lifetime of a power station. It measures the competitiveness of a power generation source and provides a useful metric to assess, rank, and quantify the feasibility of investing in different power station types.

The prediction shows clearly that fixed offshore wind has close to comparable LCOE to coal-fired generation today, and floating wind projects will have a comparable or lower LCOE than today's LCOE of coal-fired before 2040. These results indicate that floating wind will be cost-efficient compared to coal by 2040 on a global level. Also, fixed offshore wind has lower LCOE than gas-fired power stations today, and floating offshore wind is expected to achieve lower LCOE than gas-fired generation within this decade. There is little room for future technology-driven cost reduction for conventional coal- and gas-fired power stations, and future cost trends for fossil-fired power will be determined by fuel costs and carbon prices.

Figure 4-1. Averaged LCOE by power station type, DNV ETO [1]



The global averaged LCOE for fixed offshore wind is forecasted to be slightly lower than the LCOE for onshore wind by 2050, as shown in Table 4-1. This does not reflect the situation today, as onshore wind is currently less expensive than fixed offshore win. However, in the long term fixed offshore wind is expected to be cost-competitive with onshore wind. The modeling uncertainties are a result of the higher assumed capacity factor for offshore wind compared to onshore. For further ETO modeling assumptions (see Section 2.1).

Fixed offshore wind has achieved massive cost reductions over 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. NREL, in the US, recently published a report indicating that the average LCOE cost of fixed offshore wind farms commissioned from 2019 to 2020 has decreased 16% and that the LCOE is estimated to be reduced by 28%-51% between 2014 and 2020 [14]. Floating wind is expected to follow a similar (and even more aggressive cost reduction) pattern, as the market is expected to significantly mature over the next decades and to leverage significant infrastructure upgrades in multiple geographies in addition to its remarkable industrialization potential.

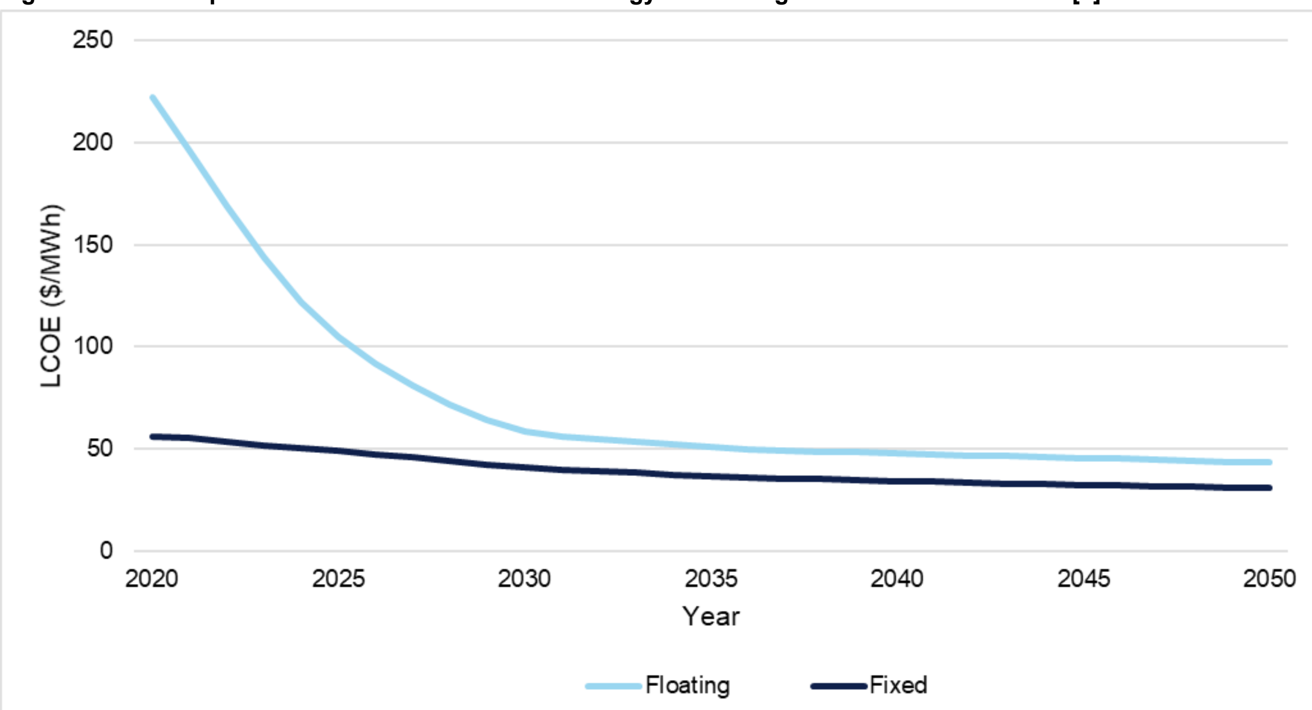
Table 4-1. Average global LCOE for onshore, fixed, and floating offshore wind. Unit $/MWh [1]

Year	Onshore wind	Fixed Offshore Wind	Floating wind
2020	63	56	222
2050	36	31	43

4.1.2 Offshore wind

Today, floating wind is significantly more expensive than onshore and fixed offshore wind; however, the LCOE for floating wind is expected to decrease by 80% towards 2050 [1]. The large, expected cost reduction is built on the assumption that the floating wind market will move from an expensive startup phase today towards a mature market in 2050. Fixed offshore wind expects a cost reduction of 44% within the same period, as this market is more mature. By comparison, onshore wind expects a cost reduction of 42% within the same period, as this market is even more mature. Today, the global LCOE for floating wind is around $222/MWh and $56/MWh for fixed offshore wind. In 2050, the LCOE for floating wind is expected to be $43/MWh. This is closer to the LCOE for fixed offshore wind, which is expected to be $31/MWh.

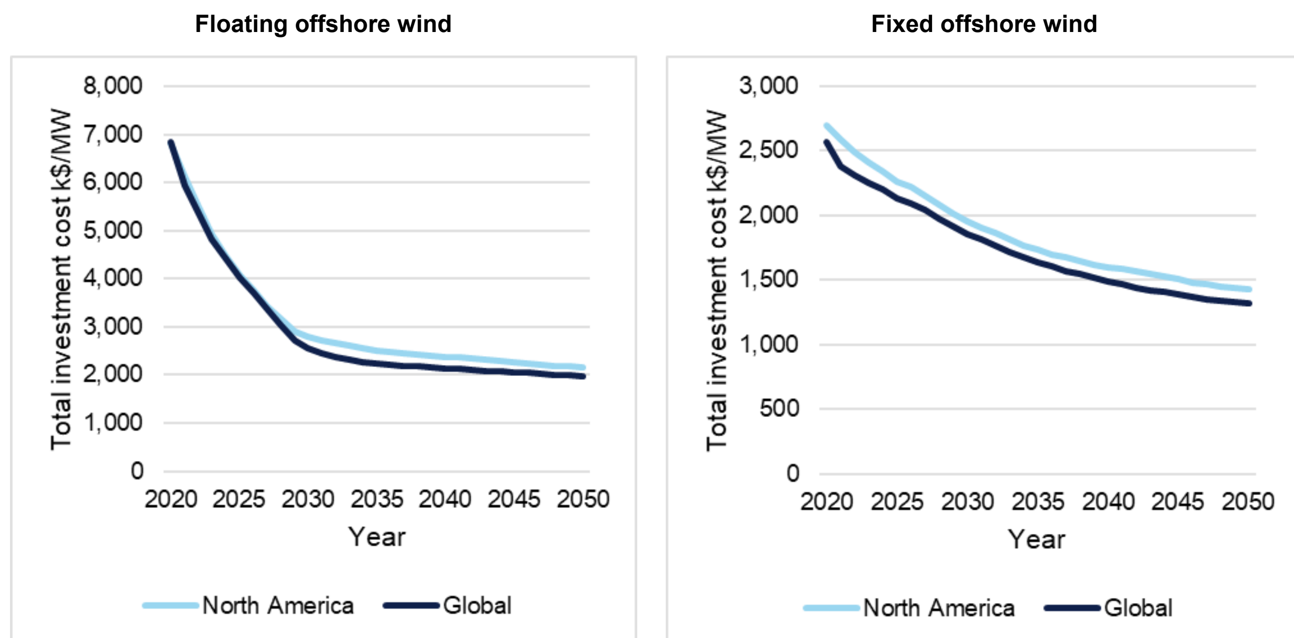
Figure 4-2. Global predictions in levelized costs of energy for floating and fixed offshore wind [1]



Cost predictions for North America indicate that LCOE will be slightly lower in this region compared to the global average. In 2050, floating wind LCOE in North America is expected to be about $40/MWh and 6% below the average global cost. LCOE for fixed offshore wind in North America is expected to be $28/MWh, which is 4% below the global benchmark [1]. The main drivers for these results are higher capacity factors and lower discount rate assumed for North America compared to other regions. Favorable wind conditions offshore in North America contribute to a higher capacity factor. The North America economy is assumed to be stable and slow growing compared to other regions, with stable policy and regulatory frameworks which is why the discount rate is assumed to be lower.

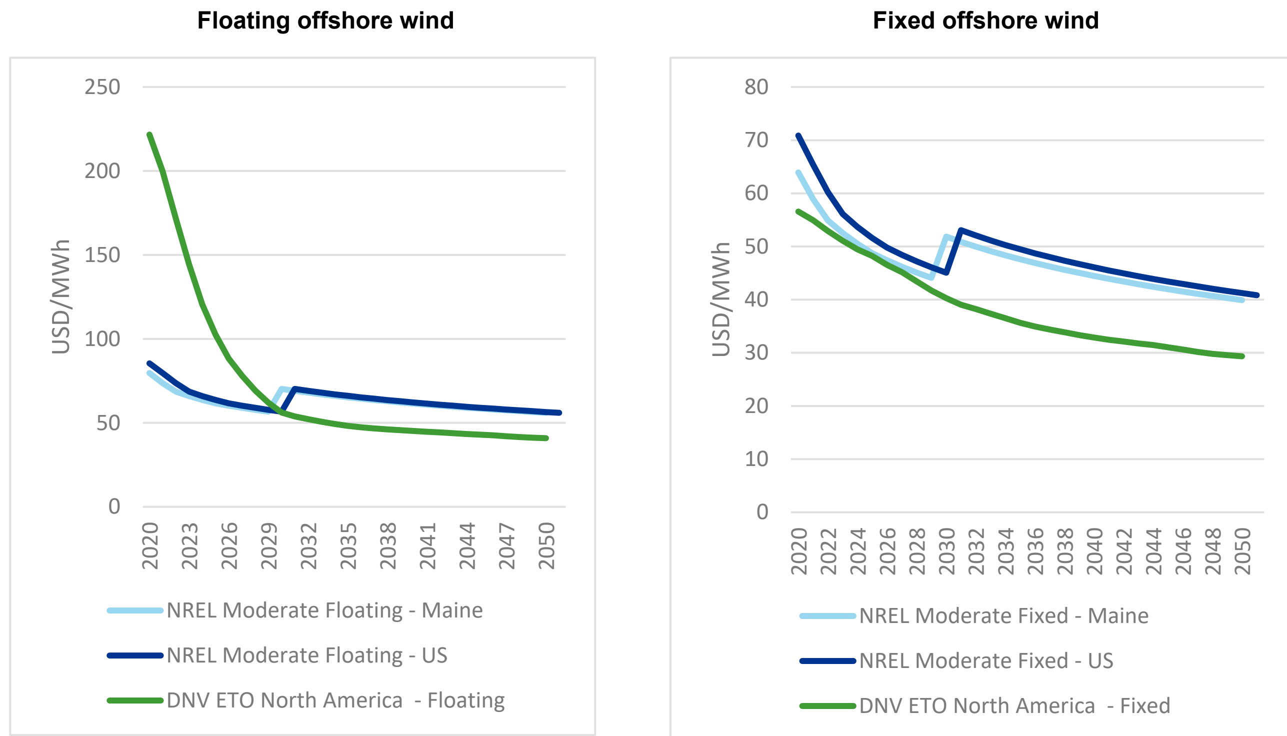
The investment cost is assumed to be higher for both fixed and floating offshore wind in North America compared to average global values, as seen in Figure 4-3. The investment costs are expected to be higher given that North America is a high-income region.

Figure 4-3. Total investment costs comparison between global and North America predictions



Wood Mackenzie has predicted the LCOE development of various energy sources for several states in the US. For Maine, floating wind is assumed to have a LCOE of $39/MWh and fixed offshore wind to reach a LCOE of $38/MWh in 2050 [7]. Wood Mackenzie's prediction for floating wind costs align with the floating wind costs predicted by DNV's ETO forecast model; however, Wood Mackenzie's prediction for fixed offshore wind LCOE in Maine is higher compared to both the global and North America predictions for fixed offshore wind provided in the ETO. The offset could be explained by the uncertainty associated with the large depths in the Gulf of Maine, which will increase the capital expenditures (CAPEX) for fixed offshore wind installation. The lack of available vessels and barges in the US, as discussed in Section 3.3.2.2, will also contribute to a significant increase of costs in the US.

Figure 4-4. NREL and DNV ETO Offshore Wind LCOEs



The National Renewable Energy Lab (NREL) also creates predictions for the LCOE of renewable energy sources for different US locations based on the resource quality in those locations. Figure 4-4 compares NREL's predictions for fixed offshore wind costs to DNV's ETO projections. The NREL predictions include the investment tax credit (ITC), whereas the ETO projections do not. Without the ITC, the NREL predictions would be consistently higher for both Maine and the overall US estimate. The reasons for this might be similar to those for Wood Makenzie's higher fixed offshore wind cost projections (see above).

Figure 4-4 also compares NREL's predictions for floating offshore wind costs to DNV's ETO projections. Again, the NREL predictions include the ITC, whereas the ETO projections do not. However, regardless of the ITC, DNV's ETO predictions are much higher in the short-term and lower (though much more similar) in the long-term. The large differences in the 2020 years likely reflect the extreme uncertainty about this nascent technology (which has yet to be installed in the US). Both long and short-term differences reflect NREL modelling strategy. NREL models floating offshore wind very similarly to fixed offshore wind, and the LCOE predictions are, in fact, fairly similar. While in the long-term, this may be the case, the costs of the new offshore wind technologies in the short-term are likely to be very high. Finally, differences are increased by the models' different assessments of annual energy production.

Other sources of difference between NREL and DNV LCOE estimates include that DNV estimates reflect the entire continent, whereas NREL estimates are either Maine-specific or US-specific. Additionally, NREL US-specific numbers are based on where these technologies are likely to be developed first, not necessarily what average costs will be over the entire geography in the long-term.

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.

Lower expected LCOE for floating wind in Maine is a result of numerous drivers, including stronger wind resources, proximity to land-based electric grid and interconnections, proximity to on-shore assembly areas, the availability of shore-based facilities and ports, and shallow and transitional water depths. These factors favor the development of floating wind in Maine, as the State has substantial shoreline with some of the greatest potential wind resources along with land-based infrastructure that currently supports other marine industries.

Table 4-2. Global, North America, and Maine [1] [3] [7] LCOE predictions in 2050. Unit: $/MWh

	Global	North America	Maine
Fixed offshore wind	31	28	38
Floating offshore wind	43	40	39

It is important to note that the limited availability of shallow waters (i.e., under 50 m) reduces the opportunity to achieve economies of scale with fixed-bottom offshore wind, resulting in an LCOE on par with floating wind (Table 4-2). As LCOE is sensitive to the industrialization ability of each technology and scale of the development, the LCOE model will be impacted by any limitations to larger scale developments.

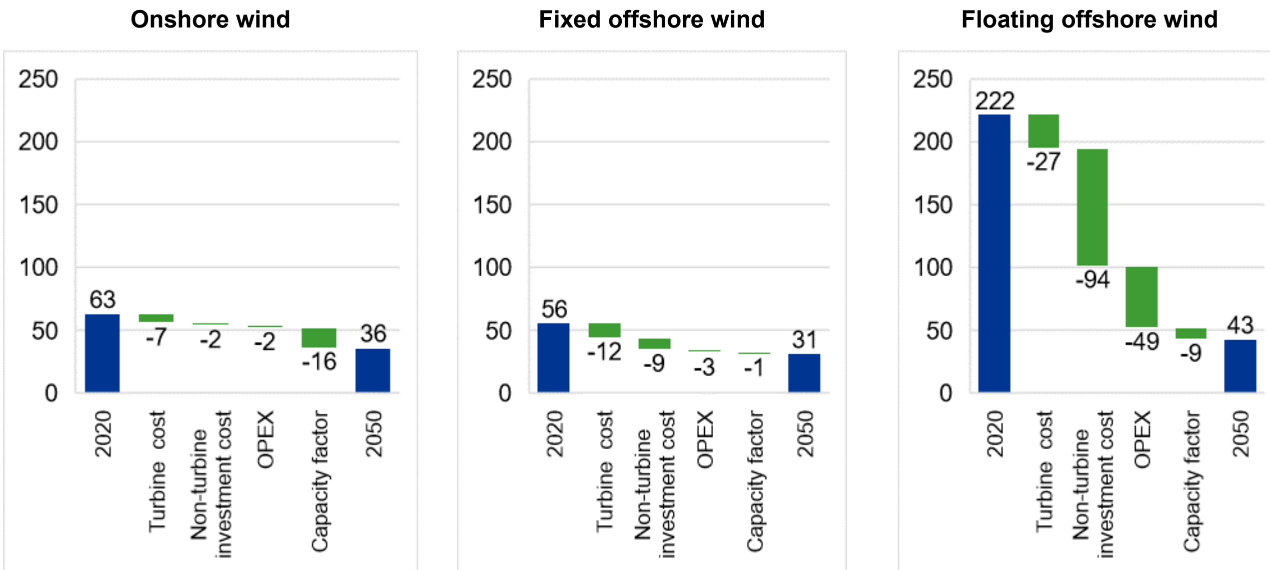
Utilizing floating wind technology in Maine has the additional potential to reduce the long-term LCOE as local construction and deployment provided the state's well-developed shoreline is feasible. Specific cost reduction could be attributed to the potential to locally manufacture and supply materials needed for platforms and sub-structures as well as reducing the distances required for connection to the electrical grid [22].

4.2 Cost components of offshore wind turbines

All price estimates in the following section are based on global trends and provide a high-level understanding of the expected cost breakdown of offshore wind. Costs are project-specific, but some general trends over time can be expected.

The costs related to offshore wind development can be broken down in two main categories – Capital Expenditures (CAPEX), which are costs related to the constructional phase, and Operating Expenditures (OPEX), which are costs related to the operational phase of the wind farm. 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. A cost breakdown comparison for onshore, fixed, and floating offshore wind is displayed in Figure 4-5.

Figure 4-5. Expected cost break down reductions towards 2050 for onshore, fixed offshore and floating offshore wind. Unit: $/MWh [1] [3]



Onshore wind is a mature technology, and new projects are expected to be developed in less favorable locations and in regions with higher costs. Hence, non-turbine related investment costs (e.g., foundation, installation, grid connection, etc.) and OPEX are expected to be only slightly reduced. Increased capacity factors and less expensive turbines are the two factors that are expected to reduce costs for onshore wind the most.

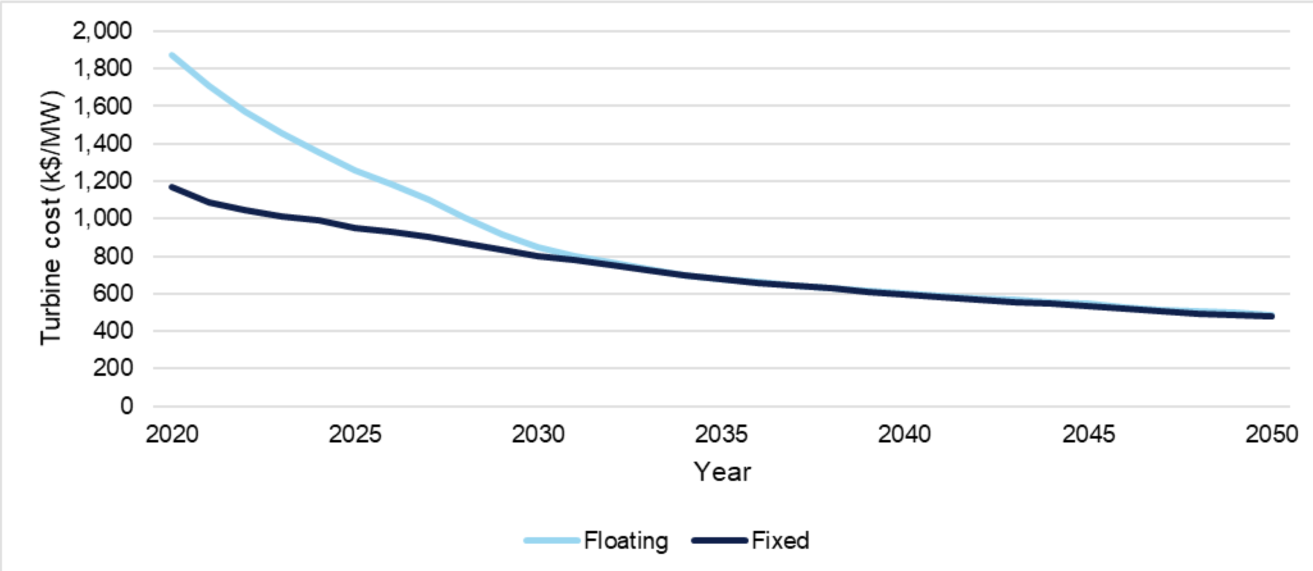
4.2.1 Turbine cost

Turbines used for fixed and floating offshore wind today are quite similar, but floating wind has a few modifications in the control system and potentially the strengthening of towers. In the short term, floating wind is expected to have significantly higher costs compared to fixed offshore turbines due to higher risks for floating wind and the fixed offshore wind is benefitting from an economy of scale. When the floating wind industry matures, it is expected that the cost of floating wind turbines will follow the same cost trajectory curve as bottom-fixed wind turbines, as the turbine technology is expected to be quite like fixed offshore wind, with minor modifications.

The turbine size is expected to increase significantly towards 2050 and turbines bigger than 20 MW are expected to enter the market during this period. The increased turbine size is not expected to play a major role in the turbine cost reduction; the biggest cost reductions are expected to come from innovation and optimization of the turbine design. Some examples on innovation from turbine designs are downwind producing turbines or vertical axis turbines, amongst others. However, the increased turbine size will impact other cost items such as installation costs and O&M costs.

[3] Excludes transmission cost

Figure 4-6. Expected global turbine cost development towards 2050 [1]



4.2.2 Foundation costs

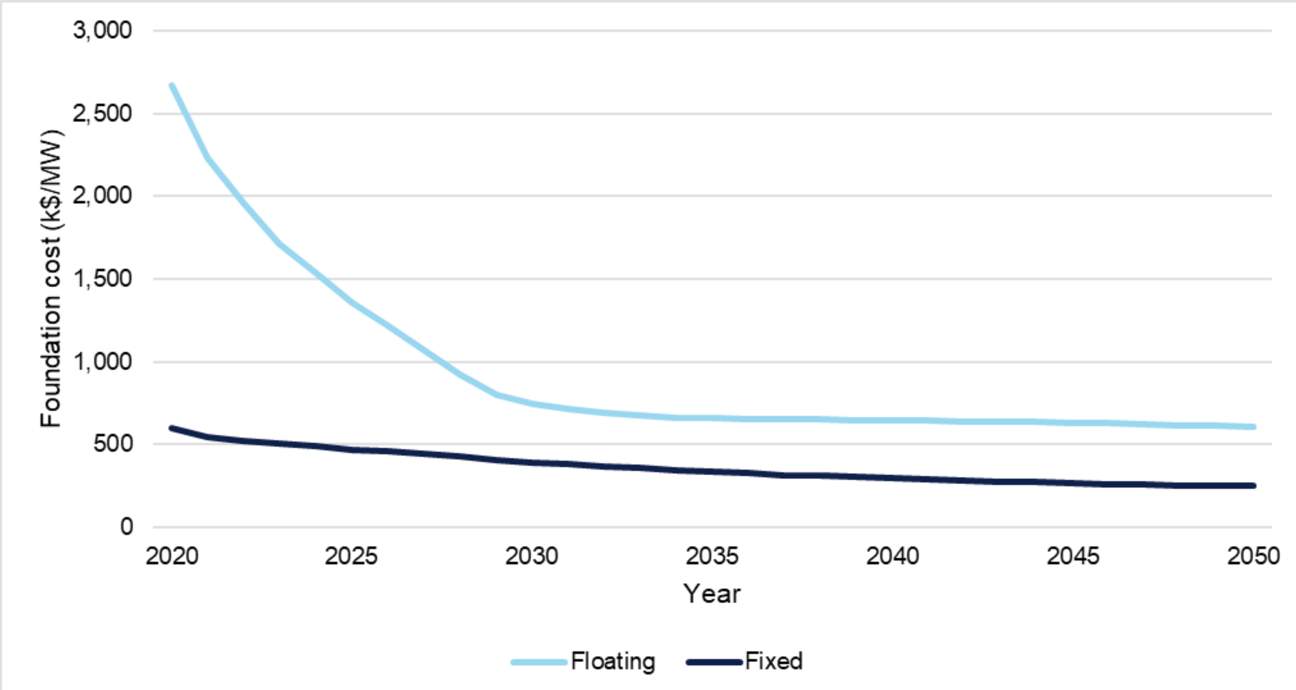
The main configurations of fixed offshore wind turbine foundations are monopile, suction bucket monopile, jacket, gravity base, and tripod; Monopiles are the lowest cost option and have been used for 80% of all fixed offshore wind turbines [37]. Foundation costs for fixed turbines are expected to decrease 60% from $528k/MW today to approximately $252k/MW in 2050.

The cost of floating wind foundations are higher than-bottom fixed foundations for several reasons. Floating wind structures typically require more material than fixed offshore wind foundations. Steel mass for the substructures used for a fixed offshore windfarm with 8 MW turbines is 1,000 ton per foundation. By comparison, steel mass for an 8 MW floating wind turbine foundation exceeds 2,000 ton. Floating foundations made using reinforced concrete are heavier still. In addition, more materials are needed for anchors and mooring systems and the foundation structures are more complex to design and fabricate. The cost of floating wind foundations are highly dependent upon the project, environment, WTG capacity output and are supply-chain dependent.

Floating wind is a new industry with currently only three operating commercial floating wind farms. Economies of scale for floating wind have yet to be realized with mostly pilot units having been deployed (UMaine, Ideol and, recently, Saitec), none of which are considered commercial wind farms nor are fully certified against an entire design life of approximately 25 years. Today, over 40 different floating concepts are under development, although four primary categories can be identified: barge, spar buoy, semi-submersible, and tension-leg platform (TLP). Section 5.3 describes each of these concepts in more detail.

The rich design field for floating wind substructures is good for innovation and technology development and over time these concepts will likely consolidate as some designs prove more successful. As the industry gains more experience and confidence in some concepts, large-scale serial production of foundations will be enabled. Shared anchor or mooring lines between turbines are other solutions for reduced costs. More turbines in a wind farm will increase the possibility for cost reductions with shared anchors and mooring lines. Therefore, the foundation cost for floating offshore wind is expected to be reduced once the size of the wind farms increases and the market matures. Foundation costs for floating wind turbines are expected to decrease about 80% until 2050.

Figure 4-7. Expected global turbine cost development towards 2050. Fixed foundation cost includes installation cost and floating foundation cost include anchors and mooring lines [1].



4.2.3 OPEX

OPEX for floating offshore wind differs from fixed offshore wind mainly due to additional inspection and maintenance of the more complex foundation and station keeping system. Major component replacement which will require the floaters to be towed to shore will also contribute to increased OPEX. Several manufacturers are working to develop solutions to conduct major maintenance activities at sea, but these efforts are in early stage research and development.

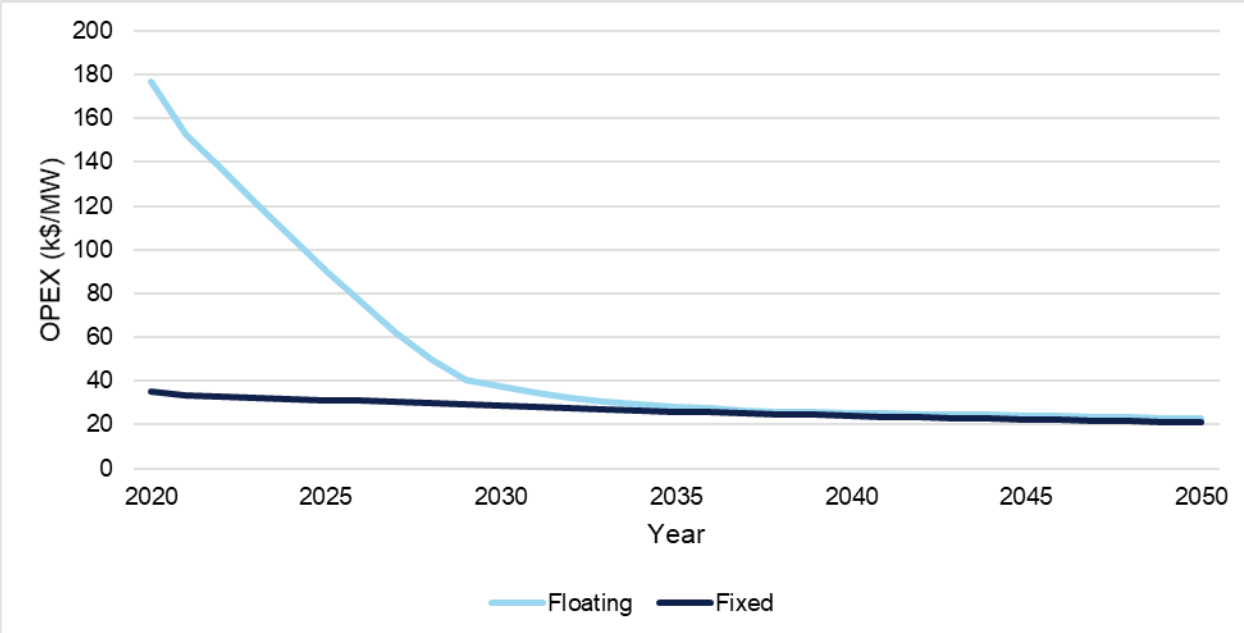
OPEX today for floating offshore wind is about 149 $/MW, which is significantly higher than fixed offshore wind, with OPEX levels of about 35 $/MW today. In the short term, floating offshore wind is expected to have a higher OPEX than fixed offshore wind, mainly driven by the currently smaller wind farms and high-risk premiums in the floating wind industry.

In the long term, floating offshore wind is expected to follow the same trajectory curve as fixed offshore wind; however, a small cost mark-up is assumed, as the floating foundations require more inspection and maintenance because floating wind farms are assumed to be further from shore and in a harsher environment compared to fixed offshore wind. The key factors contributing to OPEX reduction are turbine scaling, increased operational experience, floater inspection, and maintenance improvements.

Today, the OPEX for floating wind is more than five times as high as the OPEX for fixed offshore wind, but by 2035 the gap is expected to be reduced to about 10%. In 2050, the OPEX for floating offshore wind is expected to be 23 $/MW and the OPEX for fixed offshore wind is expected to be $21/MW.

OPEX in North America is expected to be slightly higher than the global benchmark, with OPEX for floating offshore wind equal to 26 $/MW and fixed offshore wind equal to $23/MW in 2050. The reason for this is that North America is a high price level region compared to the rest of the world.

Figure 4-8. Expected global OPEX cost development towards 2050 [1]



4.3 Floating wind cost drivers

There are several factors underlying CAPEX and OPEX costs comprising the LCOE metric for offshore wind. The following section lists and develops more on each of the most significant cost contributors within the floating wind segment. Fixed offshore wind is a more mature technology, which means that some cost reduction factors may have a larger potential for LCOE reduction specifically within the floating wind segment.

4.3.1 Larger wind turbines

Increased turbine size with larger installed capacity reduces CAPEX and OPEX costs. Whereas onshore wind starts to see an upper limit for turbine size due to transport logistic along roads, the size of offshore wind turbines is less restricted. By 2050, turbines with an installed capacity of 20 MW are expected to enter the marked; this is further described in Section 5.3.4. Larger turbines will reduce CAPEX per installed capacity, with less balance of plant work such as fewer foundations, mooring lines, and cables. Larger turbines will also contribute to reduced maintenance work per installed capacity which will bring down the OPEX.

4.3.2 Capacity factor

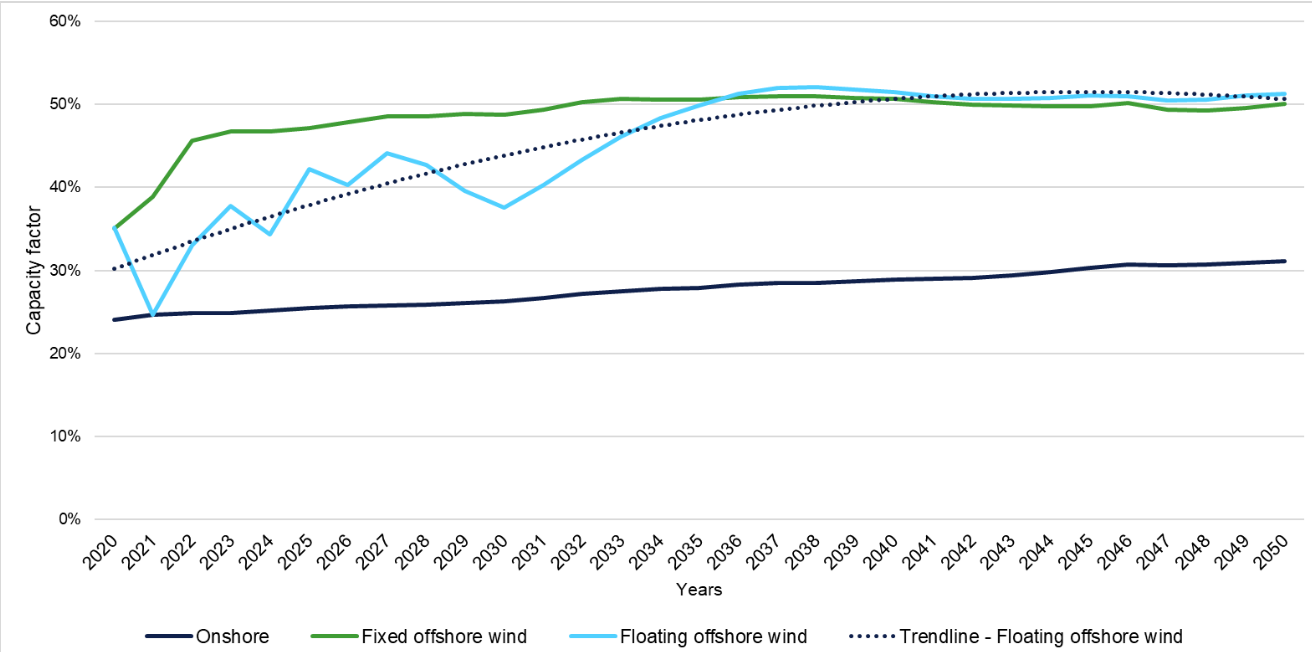
The capacity factor, defined as the average power generated divided by the rated peak power over a specified time period (usually a year), offers an indication of a wind turbine's utilization. As wind turbine development allows for better performance under varying wind conditions and with increasing turbine blade and tower size, the capacity factor of onshore and offshore installations will increase in the coming years [1].

DNV's ETO [1] modeled capacity factors for onshore, fixed offshore, and floating offshore wind from 2020 to 2050; these are presented in Figure 4-9.[4] In 2020, the capacity factor for fixed offshore wind is 35% compared to 24% for onshore wind. This difference in capacity factor is mainly due to better wind conditions and the absence of topography at offshore sites. Floating wind enables the developments of deep-water sites that have higher wind intensities than onshore or near-shore bottom fixed wind. It is therefore predicted that floating wind will have even higher capacity factor than bottom-fixed offshore

[4] Other models may reflect higher capacity factors due to different input sources and modelling strategies.

wind. The technological improvements and deep-water sites will raise the capacity factor above 50% for offshore wind by 2050, while onshore turbines will have a global capacity factor of only 30%. The fluctuation of the floating offshore wind capacity factor is due to the development of new technologies and solutions in addition to the introduction of new markets.

Figure 4-9. Capacity offshore wind worldwide forecast to 2050 [1]



Due to few installed floating wind turbines, there is little available historical data for floating wind; however, Hywind Scotland, the world's first floating wind farm, documents an average capacity factor of 54% over the first two years of operation, demonstrating the huge potential of floating offshore wind [4].

4.3.3 Larger wind farms

Development of larger wind farms contributes beneficially to optimizing the LCOE. During the construction phase, larger wind farms enable serial production which increases the efficiency and reduces time and money spent per turbine installed. During the operational phase, larger farms reduce administrative and logistics costs per turbine. Hence increased size of the wind farms will contribute to cost savings both in the construction- and the operational phase.

Today, floating wind farms are mainly pilot projects comprising one or a few turbines. The largest operating floating wind farm today is the Kindcardine phase 2 in the UK, comprising 5 turbines and a total installed capacity of 48 MW. In 2022, Hywind Tampen is expected to start operating with 11 turbines and a total installed capacity of 88 MW. Around 2030, floating wind farms of 200-500 MW size are expected to be in operation.

4.3.4 Infrastructure

Access to suitable infrastructure of ports for manufacturing and assembly as well as storage and maintenance is critical to achieving the needed industrialization for developing larger wind farms. Maine has a well-developed and extensively utilized shoreline, with ports from Kittery to Eastport. According to the Maine Port Authority, cargo shipments and other industrial infrastructure are located at the Ports of Bangor, Bucksport, Eastport, Portland Harbor, Searsport, and Winterport [27]. Figure 4-10 identifies the three main port locations in southern, mid-coast, and northeastern Maine along with a visual representation of the infrastructure supported at the locations of Portland (bottom right) and Searsport (upper right). Portland is centrally located and is the largest port in Maine while Searsport allows for convenient access to the deep waters of the Penobscot Bay region. Eastport (not shown below) is a small coastal town but is the East Coast's deepest shipping port.

Figure 4-10. Maine port locations, 2019 [27]

If there is not sufficient grid capacity available near an offshore wind farm, grid infrastructure upgrades will be needed. Upgrades to not only transmission and distribution line capacities, but substations and related infrastructure will be necessary should offshore wind projects proceed in the US. Maine is researching options for future design and operation of the electric distribution system to develop solutions that accommodate increasing amounts of renewable energy generated (from solar, wind and offshore facilities) and increase the electrification of heating and transportation sectors through modernization of the grid [53]. The Business Network for Offshore Wind published a report on grid upgrade needs in the US and noted that the northeastern US would benefit from numerous interconnection locations per offshore wind facility. Numerous interconnection locations would assist in distributing the power generated across various lines in the grid and achieving appropriate capacities for distribution [54].

4.3.5 Other Cost Contributors

4.3.5.1 Cooperation and sharing

DNV recognizes that there has been a degree of reluctance, and some protectionist attitudes, among existing and potential offshore wind industry players in the Northeast to support cooperative agreements or sharing/pooling of resources to develop the regional industry. While in some cases local and individual interests have benefitted from this strategy, consistent with many international analysts, it has been DNV's observation that the regional offshore wind industry as a whole has suffered as a result of protectionist attitudes. The Northeast region's efforts as a result have been fragmented to varying degrees, resulting in duplication of effort and potential or actual supply chain inefficiencies. As a result, much of the supply chain economic development potential that might have been built up in the region has, instead, remained in Europe.

In contrast, DNV's experience in large-scale industry development has shown that collaborative development, the sharing of resources, and the leveraging of region-specific and unique local expertise have the potential to generate a diverse, resilient industry that is able to more effectively compete on a global basis. Moreover, cooperation and sharing among entities in the industry contributes to faster learning and enables cost reductions. Examples of such entities are Carbon Trust, Offshore Renewable Energy (ORE), World Forum Offshore Wind (WFO), the Global Wind Energy Council (GWEC), for the Blue Economy generally, Washington Maritime Blue, and for regional coordination, the Environmental Business Council of New England and Business Network for Offshore Wind. To this end, DNV strongly recommends the development of joint partnerships in Maine and, to the extent possible with current political trends, across the broader region. While supply chain and equipment sourcing to date has remained largely overseas, our analysis indicates that there is still meaningful potential to enter into collaborative industry development partnerships that have the potential to greatly accelerate the industry and Maine's position in the global offshore wind economy. Maine's existing ports, which are in relatively close proximity to each other, present an opportunity for coordination and collaboration of Maine's business community to work together to develop and upgrade the ports for fabrication and assembly of floating wind foundations as well as turbine assembly and full system integration. There is opportunity to involve multiple ports, where one port may be best suited to fabricate substructure components (feasible for concrete substructures such as the Aqua Ventus semi-submersible), ship them to a second port for assembly of the foundation, while wind turbine generator (WTG) assembly may occur at a third port, and final assembly of foundation, WTG, and ancillary equipment may occur at a fourth port. Multiple port communities in Maine would stand to benefit, and this development would cement Maine as the hub for supplying floating offshore wind equipment throughout New England. By necessity, Maine has to focus on the floating market while none of the other New England states can afford to as they are occupied building out their fixed bottom areas. By the time they pivot to floating, Maine has the opportunity to have a mature supply chain ready to meet future demand of the region.

4.3.5.2 Public investment

Cost remains a critical barrier, or at least headwind, for the offshore wind market and the industry in general. While the industry is in the process of advancing significantly, including through development of more cost-effective solutions and increasing deployment rates for offshore wind, there is still considerable efficiency that could be gained through strategic public investments. For example, while the first-in-line deployments offshore of Massachusetts will help to cement offshore wind as a viable and cost-beneficial system, additional industry development such as a more robust local/Northeast regional supply chain will greatly improve implementation costs. These elements may occur organically over time as the industry develops. However, strategic early phase public investment can greatly accelerate the development of regional supply chains and other efficiency improvements. Moreover, public investment, when leveraged through public private partnerships and other mechanisms, can spur and accelerate concurrent private capital investments. For example, in Europe, the first eight floating wind pilot projects have received or will receive tariffs higher than 168 EUR/MWh (approximately USD 195/MWh), which has helped to significantly increase development of Europe's offshore wind industry more generally. Ultimately, private capital investments are the key/critical long-term growth driver for offshore wind in the region. However, carefully targeted public investment – please refer to key cost drivers indicated in Section 4.3 and industry R&D needs, Section 5 - can jump-start both offshore wind facility deployment and, more importantly, direct industry and private capital investment in offshore wind and its supply chain. In addition, federal investment tax credit (ITC) for wind does help lower the cost.

4.3.5.3 Competition

Whereas floating wind leases today typically are distributed based on qualitative assumptions, fixed offshore wind leases commonly are awarded through auctions. Auctions motivate developers to focus on cost competitive solutions and help licensors select the most cost-competitive projects. It is expected that floating wind leases will be awarded through auctions when the market matures.

4.3.5.4 Risk reduction

Risk is seen as one of the drivers for the high cost of floating wind today, but the risk premium is expected to be reduced significantly over the next several years. Lack of experience is a source of risk, but this will be reduced as developers and contractors gain experience from actual floating wind projects. The ability to choose proven floating technology when pilot projects have succeeded also contributes to reduced risks and soft costs. The development of standards and certification procedures also builds trust and reduces risk for various stakeholders. As with the onshore wind sector, interface risk related to various technology providers will decrease over time and with greater exposure. Experience gained from operational floating wind farms and an increased understanding of the required maintenance will ensure sustainable operation and lower the risk profile for projects as well.

5 INDUSTRY-WIDE R&D NEEDS

This section describes the current offshore wind industry-wide R&D needs, especially as they relate to floating technology, and assesses how Maine may help meet those needs.

5.1 R&D in the space of floating wind

The floating wind industry is still highly reliant on the R&D segment in order to advance its TRL (see Appendix B). As shown in Table 4-1, the LCOE associated with floating offshore wind turbines is expected to drop by approximately 80% over the next 30 years. This estimation of the LCOE reduction is based on the assumption that the necessary market maturity conditions are achieved. These market maturity conditions involve mainly ports and grid upgrades and a certain consistency on the necessary permitting and leasing initiatives – which are necessary to justify the infrastructure investments needed to sustain a significant pipeline of projects.

As a key contributor to this sharp cost reduction, and in combination with the above outlined market maturity conditions, the R&D industry initiatives shall target the main cost drivers of the industry. These cost drivers are further developed in Section 4.2. There are currently multiple ongoing R&D initiatives, sustained by both private industry players and public agencies, that target some of the floating offshore wind cost drivers. For an overview, some of the most significant R&D initiatives are listed, described, and clustered below by the nature of the subcomponents on which the core research work is focused.

5.2 R&D context for floating offshore wind in the US

Multiple funding agencies are currently supporting the floating offshore wind industry development through different initiatives; a non-exhaustive list is provided below.

5.2.1 ARPA-E

The Advanced Research Projects Agency-Energy (ARPA-E) is a United States government agency tasked with promoting and funding research and development of advanced energy technologies. It is modeled after the Defense Advanced Research Projects Agency. ARPA-E advances high-potential, high-impact energy technologies that are too early for private-sector investment. ARPA-E targets low TRL initiatives by seeking unique awardees to develop entirely new ways to generate, store, and use energy.

ARPA-E projects have the potential to radically improve US economic prosperity, national security, and environmental wellbeing. ARPA-E focuses on transformational energy projects that can be meaningfully advanced with a small amount of funding over a defined period.

Through the ATLANTIS team initiative, ARPA-E seeks to design radical new floating offshore wind turbines by maximizing their rotor-area-to-total-weight ratio while maintaining or ideally increasing turbine generation efficiency; building a new generation of computer tools to facilitate turbine design; and collecting real data from lab and full-scale experiments to validate the floating offshore wind turbine designs and computer tools. The program encourages the application of control co-design (CCD) methodologies that integrate all relevant engineering disciplines at the start of the design process, with feedback control and dynamic interaction principles as the primary drivers of the design. CCD methodologies enable designers to analyze the interactions of floating offshore wind turbines' aero-hydro-elastic-electric-economic-servo-system dynamics, and propose solutions that permit optimal turbine designs not otherwise achievable [1].

Prominent examples of ARPA-E funded initiatives are the development of higher output capacity down-wind turbines, vertical-axis wind turbines, and smart asset monitoring and floating offshore wind asset digitalization strategies.

5.2.2 New York State Energy Research and Development Authority

The New York State Energy Research and Development Authority (NYSERDA), established in 1975, is a New York State public-benefit corporation. NYSERDA's technology to market strategy and business innovation activities provide technical expertise and support to developers of new clean energy technologies and products to foster and grow clean energy businesses. NYSERDA's technology and business investments have helped make more than 441 new and improved clean energy products commercially available to the public [78].

NYSERDA prioritizes four growth essentials on the path to commercialization: capital; talent; market, technology and manufacturing; and network. By adopting this funding strategy, NYSERDA supports each of these essentials through different projects. In general, NYSERDA's funded programs can be considered a group of relatively higher TRL (compared to ARPA-E's) initiatives, with a stronger focus on local manufacturing and fabrication and on the actual technology-to-market strategy.

Some of the key floating offshore wind R&D initiatives funded by NYSERDA currently target the development of ancillary mooring and cable technology to increase the competitiveness level of floating offshore wind in deep, and especially, shallow-water ranges where fixed-bottom typologies could preliminarily be identified as the most appropriate foundation solution.

5.2.3 National Offshore Wind Research & Development Consortium

The NOWRDC is a nationally focused, not-for-profit organization collaborating with industry on prioritized R&D activities to reduce the LCOE of offshore wind in the US while maximizing other economic and social benefits.

This Consortium is dedicated to managing industry-focused R&D of offshore wind to maximize economic benefits of the US. The main desired impacts from the consortium are:

- Producing innovations that directly respond to the technical and supply chain barriers faced by offshore wind project developers in the US
- Building strong networks connecting technology innovators, investors, and industry
- Increasing US content and job opportunities

The Consortium was initially funded with $41 million — $20.5 million from the Department of Energy (DOE) and a matching $20.5 million from NYSERDA. Additional contributions have been made by state members including Maryland, Virginia, and Massachusetts. Collectively, the existing funds have established the Consortium for a minimum of five years. The Consortium will continue to look for other appropriate funding and R&D opportunities to build upon its initial scope [81].

5.2.4 University of Maine

The VolturnUS technology is the culmination of more than a decade of collaborative research and development conducted by the University of Maine-led DeepCwind Consortium. The University of Maine leads the DeepCwind Consortium, a unique public-private research partnership funded by the Department of Energy, the National Science Foundation-Partners for Innovation, Maine Technology Institute, the State of Maine, and the University of Maine, and includes more than 30 industry partners such as Cianbro and Maine Maritime Academy. The VolturnUS semi-submersible floating foundation technology is the culmination of more than a decade of collaborative research and development conducted by the Consortium.

The UMaine-developed and patented VolturnUS floating concrete hull technology can support wind turbines in water depths of 45 m or more and has the potential to significantly reduce the cost of offshore wind. A 2020 report from NREL determined the LCOE is < 6 cents/kWh using the VolturnUS technology at commercial scale [52].

The innovative VolturnUS design uses a concrete semi-submersible floating hull and a composite tower designed to reduce both capital costs and operation and maintenance costs, and to allow local manufacturing throughout the US and the world.

Figure 5-1. University of Maine floating semi-sub 1:8 scaled prototype

5.3 R&D initiatives in floating offshore wind

There are numerous R&D initiatives within the floating wind industry. The overarching goals of these initiatives revolve around creating cost-effective, reliable, and efficient floating concepts ready for deployment in this growing market. The R&D initiatives covered in the following sections include hull concept design developments, digitalization of assets, smart O&M, grid, transmission, and offshore substation innovations, updated WTG concepts, new approaches to offshore operations, and developments in floating offshore wind ancillary technology. These developments are founded in years of research with highly successful pilot projects in operation, paving the way for full scale deployment.

5.3.1 Hull concept development

Hull concept design, development and deployment have been significant areas of research for more than a decade in the field of floating offshore wind. The development of the first pioneering concepts (chiefly Principle Power's WindFloat and Equinor's Hywind) signified the creation of a new offshore wind industry segment around a disruptive floating foundation typology. Ever since the creation of these initial concepts, the evolution of the hull technology for floating offshore wind applications has been a constant, with a currently intense level of activity reflected by the number of hull concepts that are currently on the market. However, only a subset of these are considered to be backed up by significant track record of successful deployments (see Tier 1 concepts in Table 5-1).

The majority of the existing floating wind hull concepts can be clustered depending on the main hydrodynamic stability mechanism as either a barge, semi-submersible, spar, or tension leg platform (TLP). The barge typically features a square barge structure containing a damping pool to maintain turbine stability (see Figure 5-2). The semi-submersible hull concept typically has three joined chambers partially filled with sea water and relies on buoyancy for stability (shown in Figure 5-3). The spar buoy concept relies on gravity for stability, and extends nearly 260 ft (80 m) below the surface, as shown in Figure 5-4. The TLP design remains stable through use of a taut mooring system under tension from the positive buoyancy force of the substructure, seen in Figure 5-5. The TLP concept has a comparatively smaller footprint than other floating foundation designs [12].

Figure 5-2. BW Ideol's barge hull concept design

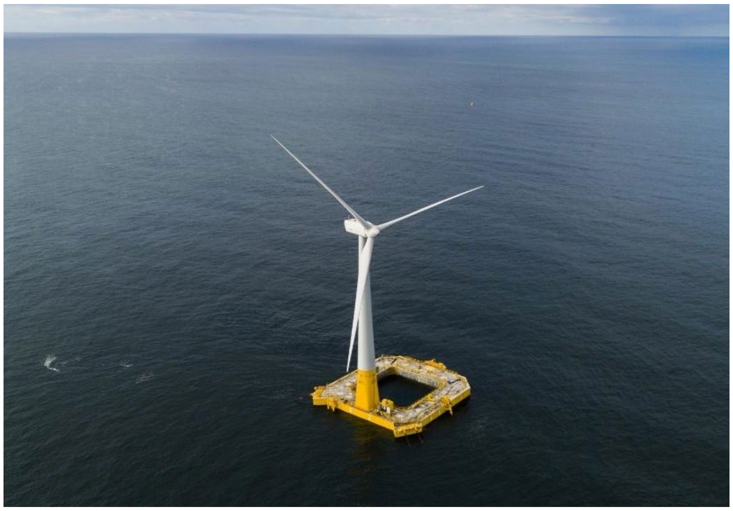


Figure 5-3. WindFloat semi-submersible design

Figure 5-4. Statoil's Hywind spar buoy design

Figure 5-5. Tension leg platform (TLP) design

Floating hull concept designs can be organized into three major tiers, Tier 1, Tier 2, and Tier 3. This categorization has been performed to gain a comprehensive understanding of industry preparedness and TRL, proven through deployment of various pilot projects.

- Tier 1 designs and developers are those with the most experience, have run successful pilot projects, and are moving towards large-scale deployment of their technology.

- Tier 2 designs and developers are those gaining momentum with smaller scale projects and promising future designs.
- Tier 3 designs and developers are incorporating more unique concepts but have not seen deployment.

Hull concept designers, their selected foundation system, and their respective tiers are provided in Table 5-1. A detailed discussion of Tier 1 and Tier 2 developments is included in Appendix A.

In general, the current state-of-the-art for hull concepts is primarily semi-submersible topologies. Semi-submersible technology derives from the oil and gas industry, has achieved a higher level of maturity than other concepts, and has gained momentum in the wind industry by early pioneers such as the WindFloat by Principle Power and UMaine's VolturnUS. However, multiple Tier 2 and Tier 3 concepts are under development with a higher range of diversity in their configurations.

For the Gulf of Maine, multiple approaches to the hull technology development are currently deemed feasible at the current stage; their applicability depends on factors like the timeline and strategy that is adopted to pursue floating offshore wind in the Gulf of Maine. Two main strategies are described below:

- A higher emphasis could be made on tier 1 semi-submersible hull concepts if the strategy of implementing high TRL solutions is a priority in the short term (within 5 years) for commercial scale deployment.
- If the applicability and project development timeline is more mid-long term (beyond 5 years), hull concepts with a lower TRL but higher potential for hull steel mass and operational optimization, such as TLP solutions, may be preferable.

Table 5-1. Hull concept designs organized by tier

Tier 1	Tier 2		Tier 3		
Ideol (B)	EOLINK (SS)	Sath (B)	Zosen (SS)	Titan 200 (Sp)	Seaplace
WindFloat (SS)	Floating power plant (SS)	Gusto Tri-floater (SS)	IHCantrilabra (SS)	Floating Hallade (TLP)	Moderic (TLP & SS)
Hywind (Sp)	VolturnUS (SS)	Dietswell/Dolfines (SS)	CETEAI (SS)	ECO-TLP (TLP)	Windbuoy
Naval (SS)	Saipem Hexafloat (Sp)	OO Star (SS)	National Maritime Research Ins. (Sp)	Ocean Breeze (TLP)	MingYang
	Toda (Sp)	Gicon (SS)	TELWIND (Sp)	Floteic (TLP)	Moss Maritime (SS)
		Tetra Float (SS)	WindCrete (Sp)	Mitsui Zosen (TLP)	Inocean (Sp & SS)
		Nautilus (SS)	Nautica Windpower (Sp)	Rosenberg Worley	X1 Wind

B: Barge **SS: Semi-Submersible** **Sp: Spar** **TLP: Tension Leg Platform**

5.3.2 Asset digitalization and smart O&M

An important cluster of R&D initiatives involves asset digitalization and smart O&M. Asset digitalization is the use of digital technologies to gain insight into and improve the operation of assets. Smart O&M involves collecting and processing condition monitoring data and using it to inform O&M strategies. The projects within this category are mainly aimed at leveraging the experience and knowledge available from already-deployed floating wind assets in order to gain more insights into the “as is” status of the units.

The initial philosophy of this R&D trend is that with a better understanding of an asset’s operating conditions, windfarm operators and designers can adjust both operating and production parameters to some extent to maximize the asset’s operational life.

Additionally, available cloud-based systems provide these initiatives with the data storage functionality that is required for in-depth analysis and processing of the recorded data. This can be especially useful for tasks like fatigue life quantification, which based on this new strategy can ultimately provide live updates of estimated remaining life based on analysis of the recorded data. A consequence of this update of the O&M philosophy is the transition from calendar-based to risk-based inspection protocols, which enables targeted repair or replacement of components with increased risk of failure, thereby avoiding both catastrophic failures as well as premature replacements, and minimizing OPEX.

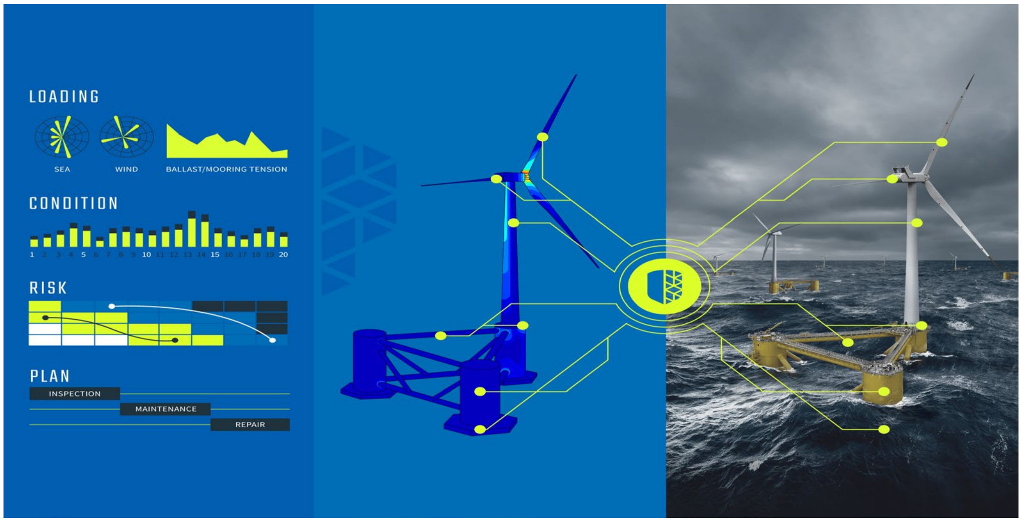
Hull, mooring and WTG design and modeling tools can also benefit from these initiatives. LCOE is reduced by maximizing WTG rotor-area-to-total-weight ratio while maintaining or ideally increasing turbine generation efficiency. Another related benefit is building a new generation of computer tools to facilitate floating offshore wind turbine design and collecting real data from full and lab-scale experiments to validate the turbine designs and computer tools [1] [2].

The main floating wind asset digitalization industry players and their respective focus areas are:

- **Principle Power** – focused on floating wind asset instrumentation and digitalization strategies, DigiFloat Project (ARPA-E)
- **Akselos** – focused on reduced-basis finite element modeling and cloud-based data analytic solutions, DigiFloat Project (ARPA-E)
- **Ocean Winds** – WindFloat Atlantic asset owner, focused on permitting and development strategies, DigiFloat Project (ARPA-E)
- **Aker Solutions** – focused on developing a digital twin model of the physical floating offshore wind turbines that could be deployed along California’s coastline, NextWind Project (California Energy Commission).
- **California Energy Commission** – currently funding the Project Inspection and Monitoring Systems for Floating Offshore Wind Applications (GFO-21-401 - Propelling Offshore Wind Energy Research, Total funding available: $4 million)

Different funding strategies similar to the funding initiatives adopted by the California Energy Commission could be adopted by Maine (or propelled by federal government policies) in order to fund and get involved in different initiatives aimed at optimizing floating wind technology’s LCOE through asset digitalization strategies.

Figure 5-6. Real time asset digitalization (Akselos, 2020)



5.3.3 Grid, transmission, and offshore substation innovation

Substations are used to increase the voltage of the electricity produced in a wind farm to reduce losses during transmission. Typical commercial-scale offshore wind projects will have one or more offshore substations installed at or near the project site. The current state-of-the-art for fixed-bottom offshore wind farms typically uses jacket foundations for offshore substations, and to a lesser extent monopiles. Substation platforms must meet strict tolerances on allowable accelerations or displacements in order for the transformers and inverters to operate properly. Typical floating wind water depths are a challenging environment for installing fixed-bottom substations, as the deeper waters require a taller foundation, which is both less able to maintain displacement and acceleration tolerances and increasingly costly as water depth increases. Hence, floating substations are presumed to be the preferred solution for deep water environments but as of yet there are no floating substations in operation. Designs for floating offshore substations incorporate added redundancy of the mooring systems and conservative substructure sizing in conformance with new regulatory standards. Given that the substation can be a single point of failure for an entire wind farm, system redundancy is critical.

Deploying a floating substation introduces higher levels of risk compared with a fixed substation, mainly associated with the following:

- Mooring line damage or failure, including anchor points
- Active ballast damage, or loss of stability resulting from substructure damage – for example boat impact
- Exceedance of design environmental conditions
- Inter-array cable damage associated with the cable hang-off configuration

The development of floating substations faces several technical challenges. High voltage dynamic cables (HVDC) must be developed, and the structural challenges related to fatigue loading must be well understood and managed. All power system components of the substation, such as the transformers, reactors, gas insulated switchgear and HVDC valves, must be qualified to tolerate the loads and environment of the floater, and their lifetime must be identified and potentially increased. A strategy for reliable and redundant lateral and vertical station-keeping through mooring configuration must be developed, as well as requirements for hook-up of power components to the floater. Potential failure modes must be understood, and standards, testing and certification schemes for floating substations must be developed.

The development timeline for floating substations is still unclear. Optimistic assumptions anticipate floating substations to be available on a commercial scale within 10 years; however, several research initiatives exist which may speed up the development.

A number of R&D initiatives in this field are under way to accelerate development of floating substations, including:

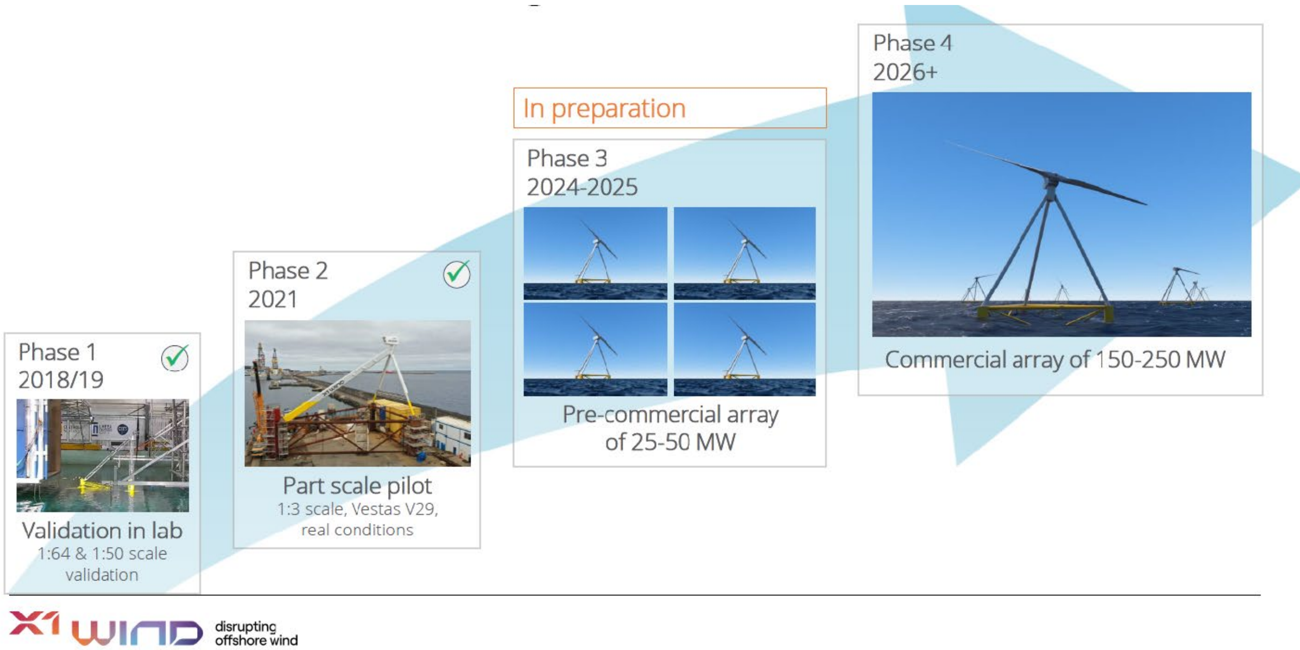
- The Green Platform Ocean Grid research study, which is being performed by The Norwegian research center SINTEF to investigate a floating HVDC platform concept.
- The Floating Offshore Wind Centre of Excellence in the UK is doing research on dynamic cables and mooring systems.
- The British organization Carbon Trust is running an ongoing joint industry project for floating wind. The goal is to overcome challenges and investigate opportunities for large-scale floating wind farms. Phase 1 and 2 of this project have been completed, which addressed key challenges for deep-water substations and dynamic cables, and provided support to 5 suppliers for development of test designs.
- DNV commenced a floating substation joint industry project in 2021 to establish an understanding and alignment of industry practice. The project intends to close gaps in standards and enable scaling of floating wind with an acceptable level of commercial, technical and health, safety and environmental (HSE) risk.

5.3.4 WTG innovation

The field of innovation within the wind turbine generator (WTG) market segment is key to reducing the floating offshore wind LCOE. The increase in WTG capacities is assumed to be a key component driving the project development and its efficiency. Therefore, the current WTG and tower configurations are scaling up to maximize output capacity—by increasing rotor diameters, scaling up rotor and nacelle components and developing new power system technology—with an associated increase of overturning loads on the foundation resulting from an increase in hub height, rotor diameter and power rating.

The current state-of-the-art WTGs impose very high loads on the floating foundations, which drives increases in cost and complexity of the WTG foundations. The current trend toward larger turbines and foundations is likely to continue for the foreseeable future, however, unless different WTG configurations are explored that increase WTG output capacity without increasing foundation loads. Given the expectation that turbine capacity is likely to eventually exceed 20 MW, multiple R&D initiatives are addressing the issue of minimizing foundation loading by integrating the foundation and tower design. One concept under development by X1 Wind and shown in Figure 5-7 is a downwind WTG and integrated tower/foundation configuration that reduces and more efficiently redistributes loads on both tower and foundations, enabling a lighter substructure [12].

Figure 5-7. X1 Wind perspective on downwind WTG capacities evolution



The X1 Wind floating pivot buoy concept leverages the advantage of integrated system design of the overall floating wind platform to increase structural efficiency and simplify the operation. Incorporating a downwind rotor enables use of more flexible blades, reducing blade loading. Replacing the tube tower with a tripod redistributes loading on both the tower legs and the foundation. The self-orienting yaw pivot buoy enables the rotor to maintain its downwind positioning, potentially eliminating the need for an active yaw system. Figure 5-8 shows a 3-bladed version of the X1 concept. Integrated systems such as the X1 concept show significant promise but will need to be thoroughly tested at full-scale as well as type-certified before they become commercially available.

Figure 5-8. X1 Wind floating prototype

5.3.5 Offshore operations

An important component of LCOE is the operations and maintenance (O&M) cost, or OPEX. As the floating wind industry is directly aimed at expanding the offshore wind capabilities to more remote and harsher environments, the cost of accessing the units for O&M purposes will tend to increase compared with fixed wind installations that are generally closer to shore.

The main driver for this increase of OPEX cost is related to safety of both personnel and equipment. Weather conditions must meet specified criteria for visibility, max significant weight height threshold and wave period correlations in order for maintenance crews to safely access the platform. A significant percentage of recorded safety incidents or accidents experienced in the fixed-bottom industry are directly related to the accessing the units.

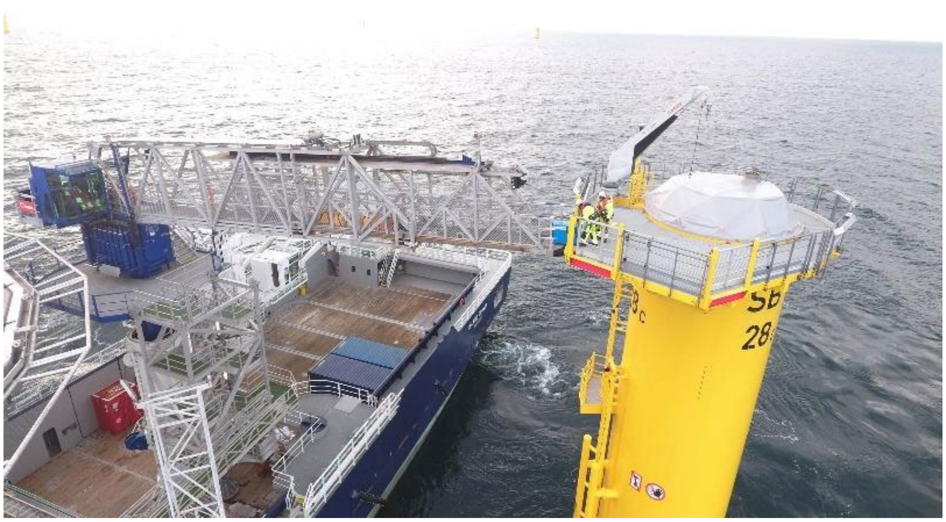
Remote inspection technology is increasingly being used in place of humans to carry out inspections, as well as some maintenance and repair tasks in harsh environments both above and below the water line. Below the water line, remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) piloted from a nearby vessel are used to visually inspect mooring lines, electrical cables, substructures and anchors. Above the water line drones are used to visually inspect rotor blades and towers. Condition monitoring, mentioned in Section 4.2.3, can also help reduce the number of ship-to-turbine crew transfers by enabling smart O&M planning and thereby increasing personnel safety. The application of remotely operated and autonomous technology to assist with operations is a nascent field, however, with much room to grow.

As previously stated, floating offshore wind is assumed to operate in remote and harsh environments, and therefore the risks stated above are assumed to persist – if not increase. This background sets the basis for the need for R&D and innovation in the field of offshore operations, in three main areas:

- Increasing the level of safety and comfort for workers involved in offshore routine maintenance activities – during which access to the offshore units are required
- Increasing the available weather window considered admissible for offshore workers to access the platforms
- Increasing use of remote inspection, maintenance, testing, and repair technologies that can be used to reduce the number and duration of in-person maintenance visits.

An important example of R&D strategy that has been implemented in the field are the “walk-to-work” telescoping walkways that are being developed by multiple companies. These are dynamically compensated bridge systems that mitigate the marine environment motions, allowing for safer access to the offshore asset from the vessel.

Figure 5-9. Walk to work motion-compensated platform



5.3.6 Floating offshore wind ancillary tech – mooring and cables

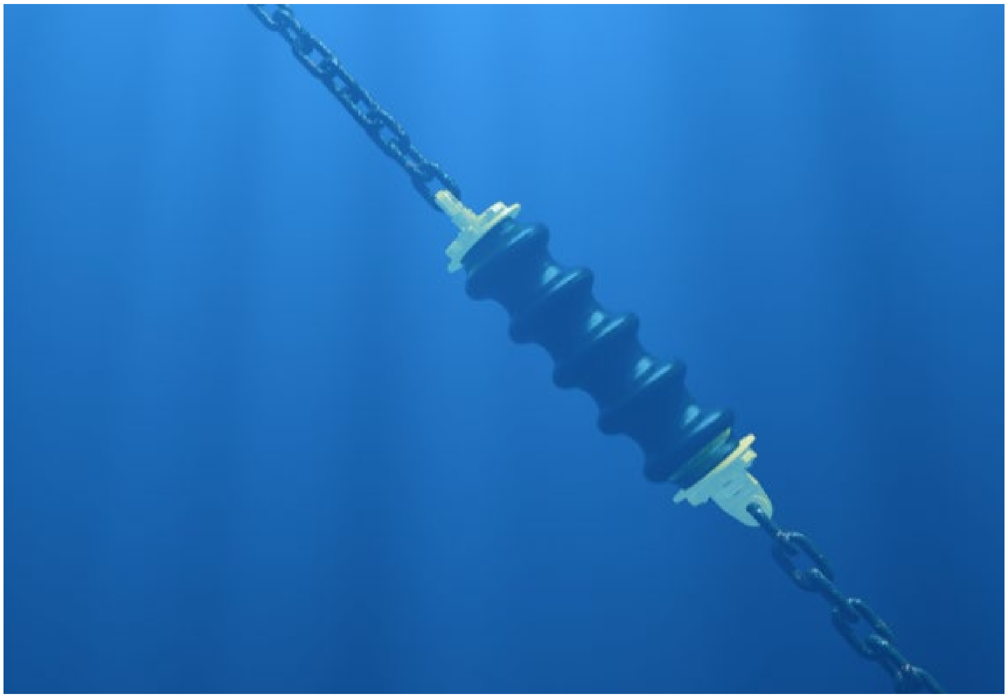
The current state-of-the-art of the floating offshore wind industry is bringing the floating technology to a higher level of competitiveness with respect to fixed-bottom. In this sense, and assuming that the deeper water depth range is solely within the realm of floating offshore wind, it is important to remark that the technology is developing to be ready to compete in transitional water depths where either fixed-bottom or floating technology could be implemented.

Multiple R&D initiatives are leveraging this idea of adapting the mooring, array and import cables, and ancillary components to make the systems suitable for transitional water depths. As an example, NYSERDA is funding shallow water related ancillary component development initiatives, which mainly act within the mooring system adaptation to shallow water depths. The main consortium players are listed below:

- **Principle Power** – focused on mooring line system development for shallow-water environment.
- **Technologies from Ideas** – focused on spring component development for absorption of higher tension ranges
- **NREL** – focused on the LCOE decrease estimation derived from the implementation of a shock-absorber component on mooring legs
- NOWRDC also funded several R&D projects related to the development of ancillary floating offshore wind technology, including **University of Maine** – Design and certification of taut-synthetic moorings for floating wind turbines
- **Virginia Tech** – tuned inverter-damper for enhanced semi-sub offshore wind turbine
- **Triton Systems, Inc.** – innovative anchoring system

The objective of the University of Maine research is to develop certified taut-synthetic moorings that ultimately could be used in Maine’s floating wind projects, presenting a potential opportunity to partner with a local manufacturer.

Figure 5-10. Mooring spring shock absorber developed by TFI [79]



6 Emerging offshore wind industry advancements and innovations

Offshore wind is an industry continuously developing, and floating wind enables a new type of market and ocean space for energy harvest and use. Industry advancements and innovations are important to bringing costs down, diversifying revenue streams, and improving solutions and application areas. In this section, we present technological solutions such as floating substations and energy islands, in addition to other technological innovations that can be combined with offshore wind, like hydrogen production, carbon capture and storage (CCS), and desalination.

6.1 Hydrogen

Hydrogen can contribute to the reduction of greenhouse gasses by replacing emitting fuels with green hydrogen, enabling the storage of renewable energy, or the long-distance transmission of energy. Offshore wind can be combined with green hydrogen production or can use hydrogen as energy storage. This section touches upon different types of hydrogen, their production methods, and the future energy demand, before presenting a selected development wind-hydrogen project.

Hydrogen demand is predicted to increase drastically as an energy carrier, from around zero in 2019 to 24 EJ/year in 2050 [1]. Energy companies and the industry are increasingly looking at offshore wind to produce green hydrogen to be used for transport, heating, industrial processes, or grid storage as a zero-emission fuel [13]. Among the renewable energy sources, offshore wind has a higher load factor than onshore wind and solar PV, which gives a better utilization rate for electrolysis [15]. Hydrogen can either be used as an energy carrier of electricity or as fuel for ships, cars, or other fuel burning processes.

There are several ways to produce hydrogen (Figure 6-1). Currently, the cheapest method is the steam methane reforming (SMR) method, blue hydrogen, which separates hydrogen from methane, and is the most cost-effective due to low gas prices. However, this method results in CO_2 emissions, which can be removed by use of carbon capture and storage (CCS), see Section 6.2 for further details about CCS. Including CCS will further increase the cost of blue hydrogen. Another possibility is to produce hydrogen without emissions as a biproduct, green hydrogen. Green hydrogen is produced through electrolysis, which is a process that splits water (H_2O) into hydrogen (H_2) and oxygen (O). Due to emission free-production, learning rates, economical scaling, and the availability of cheap electricity, the ETO predicts that by the mid-2040s this will be the dominant hydrogen production method. Brown hydrogen is produced by coal gasification, mainly in China due to the low coal prices [1].

Figure 6-1. Hydrogen color palette [12]

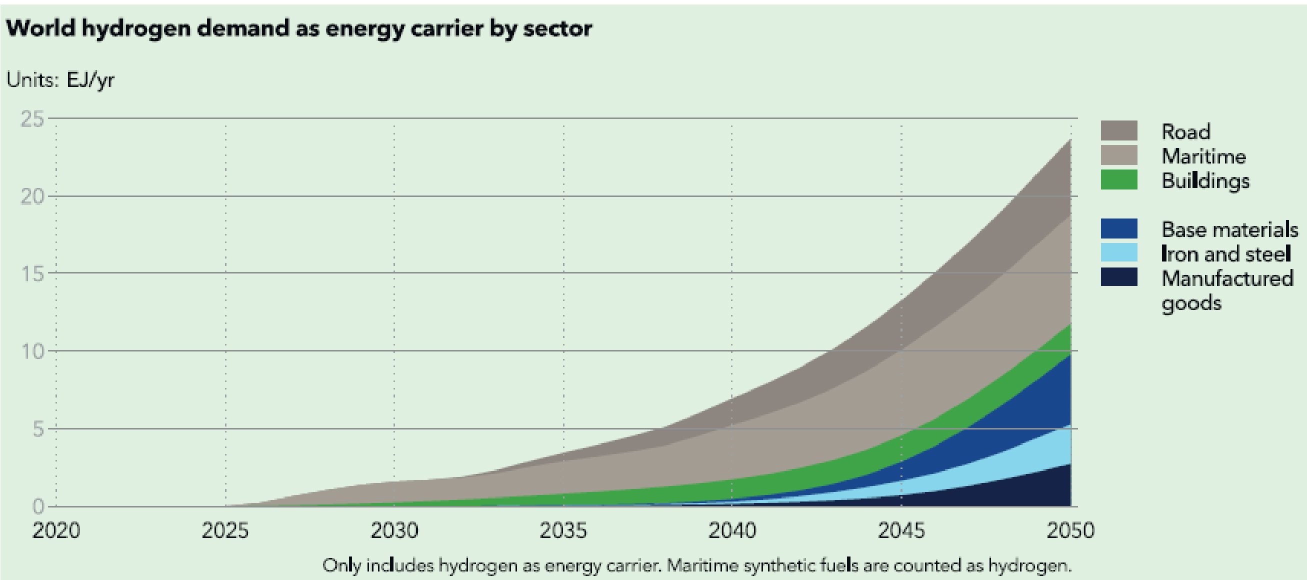
Hydrogen colour palette

Colour code	Brown	Gray	Blue	Turqoise	Green
Energy source	Coal or lignite	Natural gas	Any non-renewable energy source	Methane	Any renewable energy source
Process of getting hydrogen	Gasification	Gas reformation	Gas reformation or gasification and carbon capture & storage	Pyrolysis	Electrolysis of water
Higest to lowest greenhouse gas emissions	⟵⟶				
lowest to highest acceptance level	⟵⟶				

As hydrogen can be a low- to no-emission energy carrier, the demand is predicted to increase (Figure 6-2). All color hydrogen is expected to be in the mix to cover the increasing demand. Green hydrogen is the only emission-free alternative and large-scale electrolysis can provide more steady energy supply from renewable energy sources. In periods of extensive wind and low electricity consumption, hydrogen can be produced and stored until the electricity demand increases above the production level. Hydrogen can then be converted back to electricity through a fuel cell, although with a great loss of energy around 60-70%, and other barriers like blending with natural gas pipelines, potential increases in NOx emissions, and much lower emission reductions compared to using the green electricity directly because of efficiency loses [41].

Electrification will play an important role in the decarbonization process; however, not all industrial processes are suitable for electrification. In the cases where fuel burners can be refitted or replaced while the rest of processing equipment remains unchanged, it will be cost-efficient to use hydrogen. Examples of these processes can be found in the brick, ceramics, or glass-melting industries [1].

Figure 6-2. World hydrogen demand as energy carrier by sector [12]



Several wind-to-hydrogen projects are ongoing or initiating. Three projects that have begun or are soon to begin are presented in Table 6-1; the Deep Purple project is described further in Section 6.1.1.

Table 6-1. Selected offshore wind-to-hydrogen projects [15]

Project	Country	Operator	Capacity	Status	FID	Sanctioned	Start-Up	Linked offshore Windfarm
Q13-A Green Hydrogen Pilot Scheme (PosHYdon)	Netherlands	Neptune Netherlands	1 MW	FEED		No	Oct-21	Eneco Luchterduinen

Project	Country	Operator	Capacity	Status	FID	Sanctioned	Start-Up	Linked offshore Windfarm
H2RES Demonstration Copenhagen	Denmark	Ørsted	2 MW	Install & comm	2021	Yes	Oct-21	Avedore Holme
Deep Purple	Norway	TechnipFMC	1 MW	EPC	2021	Yes	Jan-22	

6.1.1 Deep purple

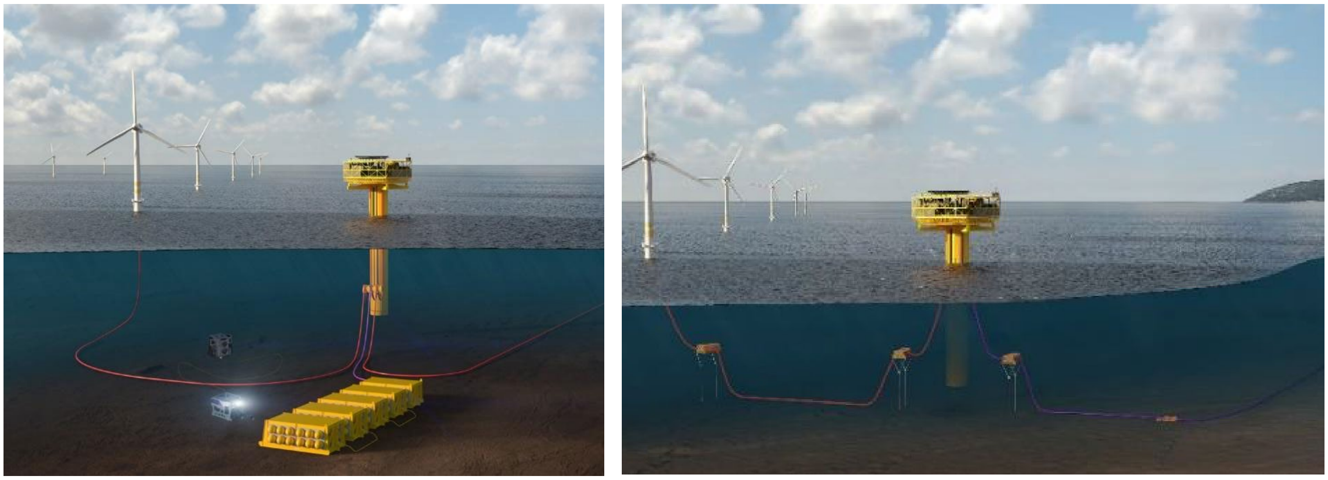
The Deep Purple Pilot is an innovative project by TechnipFMC, with partners, to investigate the feasibility of combining offshore wind with production of green hydrogen. The wind turbines can produce electricity along with hydrogen in case of excess power or can produce purely hydrogen. In either case, the hydrogen can be stored at the seabed or sent in pipes to shore. The hydrogen stored at the seabed can either be sent to land in pipes or converted back to electricity by fuel cells. The Deep Purple Pilot is limited to the following main application areas to make it beneficial:

- Supply of stable CO_2-free electric power to remote island communities
  - Target group: minimum population of 10,000 with more than 60% of fossil fuel in their energy mix
  - 35 MW power plant
- Supply of stable CO_2-free electrical power to offshore oil and gas installation
- Large scale production of CO_2-free hydrogen with pipeline export to shore for use as industrial feedstock, fuel for the transport sector such as coastal maritime traffic and other hydrogen consumers

For the first and second application area, the Deep Purple system stabilizes the electrical supply by converting stored hydrogen to electricity in times with low or no wind. Hydrogen is produced from excess power production during periods of good wind conditions and low electricity consumption, i.e., at night. The third application area produces hydrogen from a dedicated wind park and sends it to shore in pipes for fuel or other direct hydrogen consumers. Combining offshore wind with hydrogen can either stabilize the electrical supply or produce green hydrogen. The system is scalable, making it a flexible solution both for stable electrical supply and large-scale production of green hydrogen.

In principle, this concept of converting excess wind energy to hydrogen and storing it in tanks at the seabed or piping it to shore should be feasible for the Gulf of Maine; however, no details about the progress and status of Deep Purple have been released with which to compare.

Figure 6-3. Deep Purple TechnipFMC pilot project [10]



(a) Storage of hydrogen at sea bottom (b) Production of hydrogen with pipes to shore

6.2 Carbon capture and storage

Carbon capture and storage (CCS) technologies have long been considered immature and a risky distraction from other decarbonization routes, but the interest in CCS technologies has been renewed as it becomes an effective tool for achieving net-negative emissions. The International Energy Administration (IEA) Net Zero 2050 scenario requires 7.6 $GtCO_2$ to be captured annually by 2050 to be carbon neutral by that time. The status for 2020 was 26 commercial scale CCS facilities operating across the globe capturing just under 40 $MtCO_2$ [12]. In general, there exist four major types of carbon capture utilization and storages technologies, as shown in Figure 6-4.

Figure 6-4. The four major types of carbon capture utilization and storage technologies [12]

	CCS	BECCS	DAC	CCU
	Carbon Capture and Storage	Bio Energy with CCS	Direct Air Capture	Carbon Capture and Utilization
Main Purpose	Avoiding CO_2 emissions	Removing CO_2 from atmosphere	Removing CO_2 from atmosphere	Using captured CO_2 to replace the use of fossil carbon
Application	In industrial processes and power generation	In energy from biomass/waste and biofuels (ethanol)	Standalone	In concrete curing synthetic fuels, polymers, EOR, green-houses, and others
Achieve permanent CO_2 removal?	Yes	Yes	Yes, but only if the CO_2 is stored geologically or used in EOR, concrete curing and mineralization.	Yes, but only through to EOR, concrete curing and mineralization.
Contribute to circular economy?	No	No	Yes	Yes, if the CO_2 source is biogenic (ie. from biomass)

Offshore wind can be utilized in several ways to facilitate CCS. Direct Air Capture (DAC) technology extracts CO_2 from the atmosphere and requires power (e.g., from offshore wind) to operate. However, the relatively low concentration of CO_2 in ambient air (0.04%vol) presents a big challenge for DAC.

There exists mature technology for applying CO_2 capture technology to nearly all industries. The most established method is removing CO_2 from gaseous emission streams with chemical or physical solvents in a cyclic absorption-desorption cycle. The CO_2 captured needs to be stored in reservoirs, typically in the ground offshore. If the industry facility with CO_2 capture is located far from the reservoir, the CO_2 captured can be transported with ships to an offshore site location and further transmitted with pipes into the ground. Offshore wind can be used to supply power to the needed compressors to further transmit the CO_2 captured through pipes into the ground. Steady power production is required for running the compressors, which may be a challenge for offshore wind. Installing batteries can mitigate this risk.

A third option is to use offshore wind in production of synthetic fuels. Synthetic fuel is a mix of carbon and hydrogen gas. By using carbon captured from the atmosphere, synthetic fuels contribute to circular economy by not adding more CO_2 emissions to the atmosphere. Synthetic fuels are seen as a possible solution for the future aviation transport. Carbon Engineering and LanzaTech are partners in a feasibility study in the UK for utilizing CO_2 captured with DAC technology and hydrogen produced from water electrolysis to produce synthetic fuel. Offshore wind could be used as the energy source both in the carbon capture and hydrogen production.

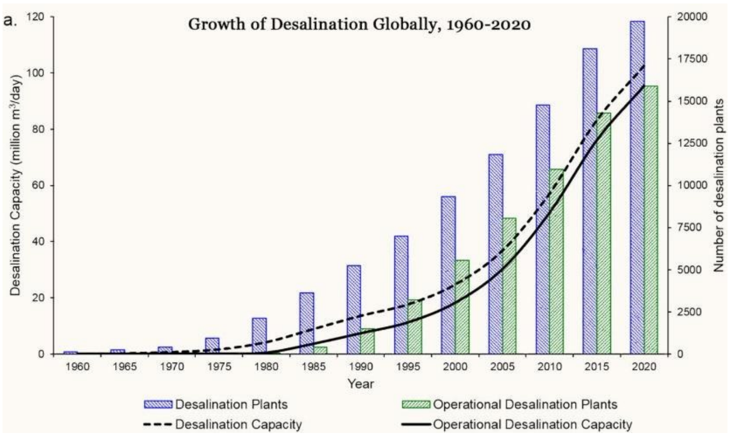
One of the key goals in the Biden Administration's "Build Back Better Agenda" is for the US to have carbon-free electricity by 2035 [11]. This is an ambitious target, which will be challenging to meet in time. DNV's ETO predicts that 24% of North America's electricity generation will come from coal and gas in 2035 and the total CO_2 emissions from electricity generation to be 720 $MtCO_2$. Only 0.9% share of the emissions is predicted to be captured. Hence, there is a huge need for more CCS development to meet the 2035 target.

6.3 Desalination

Access to fresh water is a rising challenge in the world. As the increasing population outgrows the water reservoirs and ground water is depleted or polluted, together with more extreme weather events and drought, the need for stable fresh water is more urgent than ever. While desalination may not currently be applicable to the Northeastern US, this complimentary innovation area is included for awareness of other global advancements and applications of offshore wind.

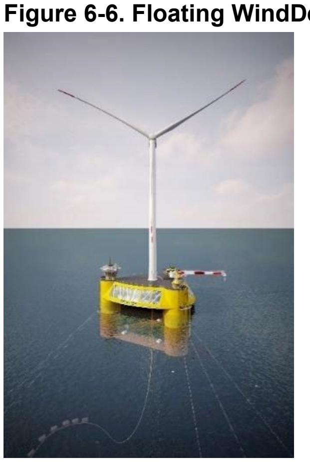
Currently, all commercial desalination plants are located onshore, but with increasing global demand (see Figure 6-5) and limited areas available close to shore, offshore desalination plants are becoming more relevant. Desalination plants require an enormous amount of energy, and in many cases, this is provided by fossil fuels. It takes two gallons of sea water to make one gallon of fresh water, leaving one gallon of extra salt water to be disposed of. To reduce the impact to marine life, the wastewater must be spread over a large area. Combining desalination with floating offshore wind can provide fresh water without the use of valuable land area (and with the use of only renewable energy), and is better positioned for the disposal of briny water. The development of floating wind makes it more appropriate than ever to consider offshore concepts for desalination.

Figure 6-5. Growth of desalination plants and capacity globally [30]



Floating WindDesal is one of the concepts being developed combining floating offshore wind with desalination. A demo is expected to be installed somewhere in the Middle East. One of the large benefits of a floating unit is that it can be reallocated by sea if needed.

Figure 6-6. Floating WindDesal module for 30,000 m3/d [31]



6.4 Energy islands/multipurpose offshore installation/power hub

The energy island is an emerging concept looking into combining several renewable energy sources to benefit from their synergies and providing steady power offshore. The power could for instance be exploited as electricity, aquaculture, the production of hydrogen, or the desalination of water. The energy island can either support the main land grid or industry with additional electricity or hydrogen, or it can be the main power installation for island communities or rural coastal areas.

The world's first energy islands are expected to be constructed outside Denmark, one in the Baltic Sea and one in the North Sea. The projects are being leaded by the Danish Energy Agencies. This exemplifies governments taking actions in the development of the renewable energy industry. Both energy islands will serve as a hub for offshore wind farms, supplying 2 GW in the Baltic Sea and 3 GW in the North Sea. The energy island in the North Sea is also planned to have a long-term expansion potential of 10 GW [42].

The installations on the energy island can be tailored to the needs of the relevant location and can consist of wind, solar PV, and wave power producing clean electricity, or in combination with e.g., desalination and hydrogen production. An example of a state-of-the-art research project is the EU founded project MUSICA. The project will develop a pilot demonstrator outside the Greek Island Innousses to increase its TRL (Appendix B). MUSICA will provide islands with up to 2,000 inhabitants with a multi-purpose platform for electricity and water.

The MUSICA MUP will include [28]:

1. Three renewable energy sources, i.e., wind, solar photovoltaic (PV), and wave, with a total of 870 kW providing a non-correlated supply of competitively affordable electricity
2. Innovative energy storage system such as water-air storage and batteries. These will be capable of providing all required storage for power on the island and platform, in addition to electrical output smoothening.
3. Smart energy system, including demand response, modeling, and forecasting
4. Renewable energy powered water desalination, capable of providing 1000 m3 of water
5. Support services for islands' aquaculture, and recharging station for electricity and water

The benefit of this concept is the synergy effect from the different renewable energy sources, the small activity area, and the joined infrastructure. While there may be opportunities for Maine, additional study is warranted here to determine the appropriate components of an applicable energy island for the region and any necessary permitting requirements.

Another example of a multipurpose platform project is the Blue Growth Farm project. This project investigates the possibilities and benefits by combining aquaculture with floating wind and wave energy on one platform. An aero-hydro prototype has recently been tested at the Natural Ocean Engineering Laboratory (NOEL) test site in Reggio Calabria, Italy [29].

Figure 6-7. Demonstration platform Blue Growth Farm [29]

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APPENDIX A: FLOATING WIND HULL CONCEPT R&D

This appendix provides additional details regarding the Tier 1 and Tier 2 hull concept designs mentioned in Section 5.3.1. Tier 1 developments are developed concepts with active, large-scale demonstration projects with pipeline(s) of additional future development planned, while Tier 2 contains less developed concepts, some with pilot projects available, that may require additional development before large scale testing can begin.

Tier 1

BW Ideol:

BW Ideol has been in the floating wind space since 2010 and in that time developed the first floating barge hull design for both wind turbines and substations. The BW Ideol design is unique in that it can be used for projects with water depths as shallow as 40 m. This design has been deployed in two demonstration projects, Floatgen off the coast of France and Hibiki off the coast of Japan, both operational beginning in 2018 [32].

These demonstration projects have identified the versatility and cost effectiveness of this barge hull concept design. The Floatgen wind turbine set a record in February of 2020 by reaching a new capacity factor of more than 66% while facing challenging weather conditions and maximum wave heights reaching almost 11 m. The Hibiki project highlighted the successful use of BW Ideol's Damping Pool® patented technology keeping turbines productive in normal conditions and stable under demanding typhoon conditions [32].

WindFloat:

WindFloat has designed a semi-submersible floating hull concept design that provides stability through anchoring to the seabed. The overall stability of this design is result of using water entrapment plates at the base of three pillars associated with a static and dynamic ballast system. The WindFloat concept can be entirely constructed and attached to a turbine onshore, decreasing offshore construction time and potentially limiting impacts to the marine environment [33].

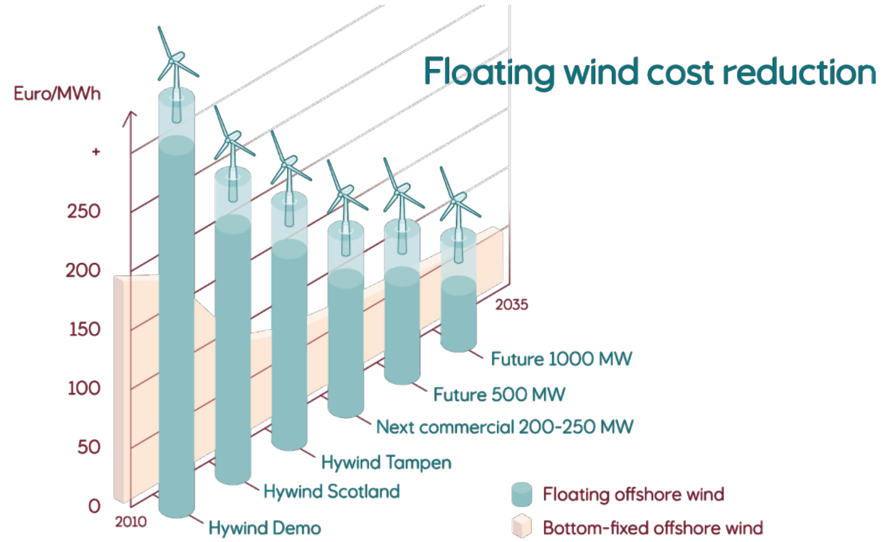
After five years of testing the technology and designs, WindFloat saw its first pre-commercial deployment. The WindFloat Atlantic project was successfully constructed in December of 2019 off the coast of Northern Portugal. This was the first project to supply floating wind power to continental Europe. WindFloat Atlantic demonstrated a low risk profile as well as economic competitiveness for this technology, making for promising future developments [33].

Hywind:

The Hywind design is a system based on a single floating cylindrical spar buoy moored by cables or chains to the seabed. The substructure is ballasted such that the entire construction floats upright. Hywind's spar design structure consists of a steel cylinder filled with ballast water and rock or iron ore with a design draft of 85 to 90 m and a displacement of nearly 12,000 tons. The buoy diameter at the water line is 9 to 10 m but has a submerged diameter ranging from 14 to 15 m. Similar to other floating designs, Hywind employs onshore assembly to reduce the time and added risk of offshore operations [34].

Hywind Scotland has achieved the highest average capacity factor for any wind farm in the United Kingdom for the third consecutive year. Eight years of testing a full-scale prototype off the coast of Norway led to a successful product able to perform well in extreme wind and wave conditions. Figure 7-1 identifies Hywind's future floating wind cost trends against future bottom-fixed trends, displaying price competition and a steady decrease in cost over time [34].

Figure 7-1. Hywind demonstrating future cost trends of their technology against bottom-fixed offshore wind projects [34]



SBM:

The SBM floating platform hull design is a lightweight steel tension leg platform. This hull concept is designed such that the majority of the structure remains submerged underwater and is anchored to the seabed under tension to minimize movement. This design consists of four buoys connected via a bracing system which then links the buoys to a transition piece holding the turbine [35].

This system has been tank tested in the Maritime Research Institute Netherlands (MARIN) and Oceanside basin facilities from 2015 to 2019. The SBM Offshore Floating Wind Technology is scheduled to deliver three 8 MW floating platforms as part of the Provence Grand Large pilot farm on the French coast of the Mediterranean Sea [35]. SBM has stated the floating concept planned for Provence Grand Large is not anticipated to require any additional construction or port infrastructure [36].

Tier 2

Below is a brief overview of Tier 2 hull concept designs, highlighting their specificities, level of maturity, and future projects planned.

EOLINK:

- Semi-submersible type stability system designed with a light, low stress pyramidal structure.
- Made up of four columns, reducing dimensions by 20% in length and width compared to a three column floating design.
- This concept is designed to gain between 20 and 25% in LCOE compared to reference floating technology [43].

Floating power plant:

- Semi-submersible type stability system.
- Floating Power Plant (FPP) has signed a Memorandum of Understanding with The Oceanic Platform of the Canary Islands (PLOCAN) to develop a potential deployment of FPP’s technology in the PLOCAN test facilities in Gran Canaria.
- Floating Power Plant is developing a global pipeline of projects, at the head of which are 2 UK projects: Dyfed Floating Energy Park in Wales and Katanes Floating Energy Park in Scotland.

- DP Energy is leading the development of these projects in which the first full-scale, FPP-platforms, units will be deployed and operated [44].

Aerodyn SCD Nezzy:

- Semi-submersible type stability system.
- The turbine is designed with a downwind rotor for self-adjustment.
- Steel ropes on the turbine head transfer and distribute the loads directly into the anchor chains.
- The downwind driven system requires no yaw bearing, yaw drives, or yaw brakes as the wind turns the turbine into the wind direction.
- SCDnezzy turbine design covers water depths between 40 and 200 m and there are no restrictions or requirements at all in terms of seabed shape and geological conditions.

VolturnUS:

- Semi-submersible type stability system.
- The VolturnUS technology is the culmination of more than a decade of collaborative research and development conducted by the University of Maine-led DeepCwind Consortium.
- VolturnUS floating concrete hull technology can support wind turbines in water depths of 45 meters or more and has the potential to significantly reduce the cost of offshore wind.
- The VolturnUS design consists of a concrete semisubmersible floating hull and a composite materials tower designed to reduce both capital and operation and maintenance costs, and to allow local manufacturing.
- According to reporting from NREL, the levelized cost of energy (LCOE)1 is < 6 cents/kWh using the VolturnUS technology at commercial scale [46].

Saipem Hexafloat:

- Spar buoy type stability system.
- The HEXAFLOAT floating pendulum concept, patented by Saipem, is currently undergoing validation.
- The HEXAFLOAT foundation is designed specifically for future large-scale offshore wind turbines with a capacity of 10 MW and beyond.
- Saipem will test a full-scale prototype HEXAFLOAT foundation at the European Marine Energy Centre (EMEC) offshore Ireland in 2022 as part of the Accelerating Market Uptake of Floating Offshore Wind Technology (AFLOWT) project [47].

Stiesdal Tetraspar:

- Spar buoy type stability system
- The project is carried out in a partnership between Shell, RWE, TEPCO Renewable Power, and Stiesdal Offshore Technologies.
- The foundation design is a tetrahedral structure assembled from tubular steel components.
- This hull concept design is expected to offer important competitive advantages with its potential for lean manufacturing, lean assembly, and installation processes, and low material costs [48].

Toda:

- Spar buoy type stability system
- The Toda Corporation (TYO:1860) has won a tender in Japan to build a 16.8-MW floating wind farm off the coast of Nagasaki Prefecture.

APPENDIX B: TECHNOLOGY READINESS LEVEL

Technology Readiness Level (TRL) as defined for hardware by the US Department of Defense in the Technology Readiness Assessment (TRA) Deskbook from July 2009.

TRL	Definition	Description
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.

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