OCS Study
BOEM 2021-030

Floating Offshore Wind Turbine Development Assessment

Final Report and Technical Summary

Task Order 140M0120F0021

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Report to:

The Bureau of Ocean Energy Management

Office of Renewable Energy Programs

Submitted by:

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The purpose of this report is to provide BOEM with an updated assessment of the technological, environmental, and economic issues related to the development of floating offshore wind turbines (FOWTs) on the Outer Continental Shelf (OCS). This report provides guidance to the staff of BOEM Office of Renewable Energy Programs (OREP) in their management of offshore wind energy leases, and environmental and technical review of proposed offshore wind facilities that utilize floating technology.

The ABSG team reviewed the current FOWT research to gather information on technical, environmental, and economic issues related to FOWTs. The assessment reviewed the current and proposed worldwide FOWT projects. The assessment also included a review of FOWT research projects and an assessment of the following technical topics:

- Structural design and dynamic modeling
- Mooring and anchoring designs
- Dynamic power cable systems
- Fabrication and installation methods
- Fabrication facilities
- Current modeling efforts

The environmental assessment reviewed issues associated with FOWTs on the OCS of California, Oregon, Hawaii, Maine, and the Atlantic Coast, as well as projects in the United Kingdom (UK) and Norway. Research indicates three broad categories of environmental issues unique to FOWTs for BOEM to consider when determining whether to grant a lease to private developers for FOWT construction: fishing, shipping/navigation, and pelagic life.

1. Loss of access to shipping grounds, negatively impacting both displaced fishers and the areas to which those fishers are displaced
2. Shipping/Navigational hazards, including the need to alter shipping routes to avoid the risk of collision/allision
3. Impacts of the FOWTs on pelagic life, namely entanglement, habitat displacement, spill risks, and noise impacts

The economic assessment reviewed the published studies of FOWTs in several areas, including wind speeds in proposed and potential areas, projected technological advancements in the FOWT industry, availability of local infrastructure for the fabrication & installation of FOWTs, as well as for grid interconnection, and local regulatory conditions. The assessment included the economic feasibility of FOWT sites on the OCS in California, Oregon, Hawaii, Maine, and the Atlantic Coast.

Based on the finding from this study, ABSG recommends the following additional research and actions to further the advancement of FOWTs on the OCS:

- Currently, the existing AWEA Offshore Compliance Recommended Practices (AWEA OCRP, 2012) are outdated. AWEA is developing a new set of recommendations practices, which they plan on publishing in late 2021. The recommended practices will include recommendations for floating offshore wind systems, deployment, and operation. BOEM should be aware and track the development of the recommended practices, associated standards and guidelines by AWEA/ANSI and other standards development organizations and investigate the incorporation of the documents into regulation by reference.
- BOEM should follow current ongoing research projects detailed in this report on technological, environmental, and economic issues and use project results to inform the development and environmental reviews of WEAs, and the technical and environmental reviews of Site Assessment Plans, Construction and Operations Plans, Facility Design Reports, Fabrication, and Installation Reports.
- BOEM should consider conducting further studies to identify fishing areas in and around current and future Call areas and assess potential impacts to fishing. The research should include types of fishing that occurs, species targeted, fishing gear used, depths fished using certain gear, and space required for the types of fishing.
- BOEM should coordinate with NOAA Fisheries, USCG Waterways Management, state fisheries, and the fishing industry using all available means, including AIS/VMS data, vessel trip reports, and other fisheries information to determine fishing transit routes and high- and low-density fishing areas and impacts of fishery displacement.
- BOEM should collaborate with wind farm developers, NOAA, state fisheries, and the fishing industry to research wind farm designs and fishing methods that accommodate fishing within wind farms.
- BOEM should ensure that developers consult with the U.S. Coast Guard and waterway users to consider project-specific factors such as vessel traffic patterns and fishing activities that occur in and around the FOWT project sites to inform the design of mooring systems and dynamic power cables in order to minimize navigation impacts.
- BOEM should encourage the State of Maine to work with USCG Waterways Management on vessel traffic and safety of navigation issues as the state seeks to identify the specific site for the proposed research array to avoid impacts to navigation and shipping.
- BOEM should request the USCG Waterways Management conduct Port Access Route Studies (PARS) for central and northern California, Oregon, Hawaii, and the Gulf of Maine to identify and analyze current maritime traffic, routes, and vessel traffic densities to determine the potential impacts from offshore wind development. BOEM could use the results of the PARS to evaluate current and future Call areas and WEAs, including the proposed Maine floating offshore wind research array.
- BOEM should conduct additional research into infrastructure requirements for FOWT development (fabrication, construction, assembly, operations & maintenance) to include

potential ports, supply chain, navigation, and transmission grid connections. This research would identify and promote technical solutions, improve the interactions between the industry and government agencies, facilitate the development of renewable energy supply chains, and continue to assess the effects of development on the environment and economy.

1 INTRODUCTION

The purpose of this report is to provide BOEM with an updated assessment of the technological, environmental, and financial issues related to the development of floating offshore wind turbines (FOWTs) on the Outer Continental Shelf (OCS). This report provides guidance to the staff of BOEM Office of Renewable Energy Programs (OREP) in their management of offshore wind energy leases, and environmental and technical review of proposed offshore wind facilities that utilize floating technology.

The goal of the study is to provide a current assessment of the FOWT industry for potential development on the OCS, primarily in the Pacific Region as well as the Gulf of Maine. The purpose of the study is to inform BOEM OREP staff in their management of wind energy leases and environmental and technical review of proposed floating offshore wind farms.

This report includes the following objectives:

1. Collect and review available information on existing and proposed FOWTs, and ongoing research efforts. Collect and review data on potential FOWT sites on the OCS, infrastructure capabilities and needs, relevant environmental issues.
2. Assess collected data to determine the potential for FOWT projects on the OCS in the next 5 to 10 years, including most likely sites, anticipated problems to resolve, and potential issues for BOEM.
3. Submittal of a report based on the above research that informs and provides BOEM information on better management of current and future lease areas and technical and environmental review of FOWT facility plans and designs.

2 METHODOLOGY

Using publicly available information, the ABSG team collected information on current and planned FOWT projects and FOWT research from reputable research programs, national labs, and academic institutions. Our review primarily focused on those projects that are currently in operation or under construction or have advanced to the level with confirmed financing and/or regulatory approval. The selected projects included in the review cover broad geographic areas and a variety of FOWT designs and developers.

The analysis methodology incorporates domestic and international knowledge from private industry, academic experts, and government agencies. Additionally, the analysis considers the specific geologic, environmental, and industrial conditions in the U.S. OCS.

ABSG utilized materials from ABS's experience with FOWTs, including participating in several research projects funded by the DOE ARPA-e ATLANTIS program and NYSERDA, as well as providing advisory support to wind energy related research projects in Europe, such as Floating Wind JIP (Phase 1) managed by Carbon Trust. ABS is also actively working with designers, developers, and regulatory agencies on FOWT design review and certification.

This report summarizes FOWT projects and research highlighting the prime issues of concern for BOEM and provides links to sources of available data. The study assesses the potential application and significance of current and potential FOWT projects and research on developing FOWT on the U.S. OCS. The assessment includes potential technological challenges, environmental challenges, and economic feasibility. The assessment results are used to develop the final recommendations for FOWT development for BOEM described in Section 7.

3 RESEARCH

The ABSG team reviewed the current FOWT research to gather information on technical, environmental, and economic issues related to FOWTs. The U.S. and worldwide projects are summarized in Sections 3.1 and 3.2. Section 3.3 provides additional detail on specific projects. Finally, Section 3.4 provides a description of the design concepts and features of the FOWTs.

The team collected information for all FOWT projects from publicly available sources, such as public media and news announcements. Most of the projects, especially installed projects, have project specific websites, providing additional context. Among them, project sources were cross-checked to ensure accurate information. For some projects, which were proposed several years ago but were canceled or halted, no new information was available. These projects are still included for a complete assessment.

3.1 FOWT PROJECTS – UNITED STATES

Currently, there is one (1) installed FOWT project and ten (10) planned projects in the United States. The first operational FOWT installed and connected to the grid was a small scale 1:8 VolturnUS developed by the University of Maine. Table 1 provides a summary of the project information.

Several FOWT projects are under planning and development in the U.S. Among them, there are two projects planned to be deployed in state waters, the "New England Aqua Ventus I" project in the state water in the Gulf of Maine, and the "CADEMO" project in the state water offshore California. Since 2016, the Bureau of Ocean Energy Management (BOEM) has published four wind energy Call for Information and Nominations (Call) areas on the Outer Continental Shelf for FOWTs in federal waters. Since then, several projects have been proposed in these call areas. Table 2 contains a summary of the BOEM call areas.

In addition, with some of the highest sustained wind speeds in the world, the OCS of the Gulf of Maine has great potential for generating clean energy and economic opportunity for Maine. The state of Maine intends to file an application with the BOEM for a floating offshore wind research array, located in the Gulf of Maine, to advance new technology in collaboration with Maine's fishing industry. As envisioned, the research array would be located some 20 to 40 miles offshore into the Gulf of Maine, in an area that would allow a connection to the mainland electric grid in the southern half of the state. The research array is expected to contain a dozen or fewer floating wind turbines over approximately 16 square miles of ocean or less. By comparison, commercial offshore wind lease areas elsewhere along the East Coast are frequently greater than ten times this size.

Table 1 FOWT Projects – U.S., Installed

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
2013	VolturnUS 1:8	VolturnUS, semi-submersible	Offshore Castine, Maine, US	Renewegy 20 kW	University of Maine	Small scale prototype demo	Decommissioned in 2014

Table 2 BOEM Call Areas for Floating Offshore Wind Farm (FOWF) Leases

Year	Call Area	Location	Map
2016	Oahu (North, South)	Offshore the Island of Oahu, Hawaii	Link to Map
2018	Humboldt	Offshore Northern California	Link to Map
	Morro Bay Diablo Canyon	Offshore Central California	Link to Map

Table 3 summarizes the projects in the planning and development phases in both state waters and federal waters.

Table 3 FOWT Projects – U.S., Under Planning/Development

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
2013	WindFloat Pacific (WFP)	WindFloat semi-submersible	Offshore Coos Bay, Oregon, US	5×6 MW	Principle Power	Pre-commercial	Cancelled
2023	New England Aqua Ventus I	VolturnUS semi-submersible	Offshore Monhegan Island in the Gulf of Maine, US	12 MW	University of Maine	Prototype demo	Expected to be completed in 2023
2024	RedWood Coast	WindFloat semi-submersible	Offshore Humboldt County, California, US	100 – 150 MW	Principle Power	Commercial	BOEM Call Area Expected to come online in 2024
2025	Progression South	WindFloat semi-submersible	Offshore Oahu, Hawaii, US	400 MW	Principle Power	Commercial	BOEM Call Area Plan proposed
2025	CADEMO	SBM TLP/ Saitec SATH	Offshore Vandenberg, California, US	4×12 MW	SBM Offshore/ Saitec	Pre-commercial	Planning for operation by 2024/25
2026	Castle Wind	No data	Offshore Morro Bay, California, US	1000 MW	No data	Commercial	BOEM Call Area Planning for 2026
2027	AWH Oahu Northwest	WindFloat semi-submersible	Offshore Oahu, Hawaii, US	400 MW	Principle Power	Commercial	BOEM Call Area Plan proposed

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
2027	AWH Oahu South	WindFloat semi-submersible	Offshore Oahu, Hawaii, US	400 MW	Principle Power	Commercial	BOEM Call Area Plan proposed
No data	Diablo Canyon	No data	Offshore Diablo Canyon, California, US	No data	No data	Commercial	BOEM Call Area
No data	Mayflower Wind	No data	Offshore Massachusetts, US	10+ MW	Atkins	Prototype demo	Planning

3.2 FOWT PROJECTS - INTERNATIONAL

International FOWT projects are summarized in Table 4. As of 2021, there have been 14 installed FOWTs and 41 proposed projects worldwide and a total of 80.8 MW install capacity of FOWTs worldwide including the 7MW FOWT, Fukushima Floating Offshore Wind Farm Demonstration Project (FORWARD) Shimpuu, which was dismantled in 2020. Detailed information on the proposed and installed projects can be found in Appendix A.

- Europe is active in the development of floating offshore wind energy. In Denmark, the “Poseidon 37 Demonstrator” project is a hybrid wave/wind energy project by Floating Power Plant. The designer is developing an upscale design called “P80” for floating wind energy projects.
- France has one project in operation, and several projects are under planning/development. Among them, the four pilot FOWT projects, EFGL, Groix & Belle-Ile, EolMed, and PGL plan to apply four different floating substructure technologies in the pilot projects.
- Germany has one proposed project with a Tension Leg Platform (TLP) concept.
- Ireland has two proposed projects.
- Norway has the world’s first full-scale FOWT installed in 2009 and five projects under planning/development.
- Portugal has the world’s first full-scale WindFloat semi-submersible FOWT installed in 2011, which was decommissioned in 2016 and relocated to the Kincardine floating offshore wind farm (FOWF) in the UK in 2018. Portugal also has the world’s largest FOWTs installed.
- Spain has two installed and decommissioned small-scale multi-turbine FOWT and several proposed projects.
- Sweden has one small scale vertical axis wind turbine installed in 2015.
- The UK has the world’s first FOWF Hywind Scotland installed in 2017, the world’s largest FOWF Kincardine under construction, and a few other projects under planning/development.

- There are increased development activities in FOWTs in Asia. Japan has several pilot FOWT projects to demonstrate different design concepts. The Fukushima FORWARD project has the world's first and only floating substation at 66 kV voltage. There are also a few projects under planning and development.
- Korea has two demonstration projects and a few commercial FOWF projects under planning/development.
- Taiwan has a few FOWT projects in the planning phase.

Table 4 FOWT Power Capacity - Worldwide

Country/Region	Installed		Under Planning/Development	
	No. of projects	Power (mw)	No. of projects	Power (mw)
Total	14	80.8	43	4,639.7
U.S.	1	0.02	10	2,420.0
Denmark	1	0.033		
France	1	2	5	112.3
Germany			1	2.3
Ireland			2	106.0
Norway	1	2.3	5	102.6
Portugal 1)	2	25.2		
Spain	2	0.23	6	102.2
Sweden	1	0.03		
UK 2)	2	32	3	162.5
Japan 3)	3	19	3	26.0
Korea			7	1,605.8
Taiwan			1	

Notes:

1) 2 MW WindFloat 1 (WF1) decommissioned in 2016, relocated to UK Kincardine wind farm in 2018
2) 47.5 MW (5×9.5 MW) in Kincardine wind farm are to be installed
3) 7 MW Fukushima Shimpuu will be dismantled in 2020. The 22 MW Goto city wind farm under planning is an extension of the 2 MW Sakiyama wind turbine project already installed.

3.3 FOWT PROJECT SUMMARIES

As floating wind turbine technology is attracting increasing attention from the energy market, there are many new concepts and project proposals with a wide scatter in the level of maturity. Our review primarily focuses on those projects that are currently in operation or under construction or have advanced to the level with confirmed financing and/or regulatory approval. The selected projects also cover broad geographic areas, FOWT designs, and developers as possible such that the diversity of the FOWT projects and technologies can be addressed in the review. These projects represent different design concepts and features. Among all the projects listed in Section 3.1 and Section 3.2 (Appendix A), we have reviewed the following projects in depth with a detailed summary of each project is provided in Appendix B:

- Redwood project to address the U.S. West Coast
- Aqua Ventus project to address the U.S. East Coast
- First U.S. small scale demonstration project VolturnUS 1:8
- Other U.S. proposed projects for U.S. West Coast
- Hywind demo project for the first full scale floating wind turbine
- TetraSpar Demo project to address Steisdahl
- The four French test projects, EFGL, Groix & Belle-Ile, EolMed, and PGL
- Hywind Scotland and Tampen
- Donghae project to address Hexicon in South Korea
- WindFloat Atlantic (WFA) and Kincardine in Europe
- WindFloat 1 (WF1) to address scalability and relocation
- Ideol France and Japan to address different materials
- Fukushima FORWARD floating wind project
- Saitec to address one more unconventional design (SATH or DemoSATH)
- Other installed full-scale demonstration projects
- Small scale demonstration projects

Currently, there are several demonstration FOWTs, and two pre-commercial FOWFs (Hywind Scotland and WindFloat Atlantic) installed worldwide. These projects provide valuable data on the design, construction, and installation of the FOWTs. This information, data, and experiences are valuable for the future development of commercial floating offshore wind farms.

3.4 SUMMARY OF DESIGN CONCEPTS

Different designs of floating substructures of the projects, including a few still at the development stage with no project planned in the near future, are summarized in this subsection. A summary of design concepts is given in Table 5. The different design concepts with related projects are summarized in Sections 3.4.1 through 3.4.28. The available data and figures provided in the summaries are from publicly sourced information, such as industry and project websites, research reports, and project reports and cataloged in Section 8 References, Section 9 Additional Resources, and Appendix B. FOWT Project Summaries.

Table 5 Summary of FOWT Design Concepts

Type	Concept	Development Stages
Spar-type	Hywind	Installed
	Toda Hybrid Spar	Installed
	Fukushima FORWARD Advanced Spar	Installed
	SeaTwirl	Installed
	Stiesdal TetraSpar	Under development
Semi-submersible-type	WindFloat	Installed
	Fukushima FORWARD compact semi-submersible	Installed
	Fukushima FORWARD V-shape semi-Submersible	Installed
	VolturnUS	Installed
	Sea Reed	Under development
	Cobra semi-spar	Under development
	OO-Star	Under development
	Hexafloat	Under development
	Eolink	Under development
	SCD nezzy	Under development
	Nautilus	Under development
	Tri-Floater	Under development
	TrussFloat	Under development
Barge-type	Ideol Damping Pool barge	Installed
	Saitec SATH (Swinging Around Twin Hull)	Installed
TLP-type	SBM TLP	Under development
	PivotBuoy TLP	Under development
	Gicon TLP	Under development
	Pelastar TLP	Under development
	TLPWind TLP	Under development
Multi-turbine platform	Hexicon multi-turbine semi-submersible	Under development
	W2Power	Installed
	Floating Power Plant	Installed

3.4.1 Hywind

Hywind is a floating wind turbine design based on a single floating cylindrical spar buoy moored by cables or chains to the seabed. Its substructure is ballasted so that the entire construction floats upright. Hywind combines familiar technologies from the offshore and wind power industries into a new design.

Figure 1 FOWT Design Concept - Hywind

- **Designer:** Equinor
- **Type**: Spar
- **Hull Material:** Steel or concrete
- **Mooring System:** Spread mooring system
- **Project:**
    - Hywind Demo – 2.3 MW Capacity (Installed)
    - Hywind Scotland – 30 MW Capacity (Installed)
    - Hywind Tampen – 88 MW Capacity (Under development)
    - KNOC (Donghae 1) – 200 MW Capacity (Under development)

3.4.2 Toda Hybrid Spar

Toda hybrid spar is a hybrid spar-type floating platform consisting of a lower section of prestressed concrete and an upper section of steel. Figure 2 provides a schematic of the spar with the concrete lower section (gray) and the upper steel section (yellow).

- **Designer:** Toda
- **Type**: Spar
- **Hull Material:** Steel and concrete hybrid
- **Mooring System:** Spread mooring system
- **Project:** Sakiyama – 2 MW Capacity (Installed)

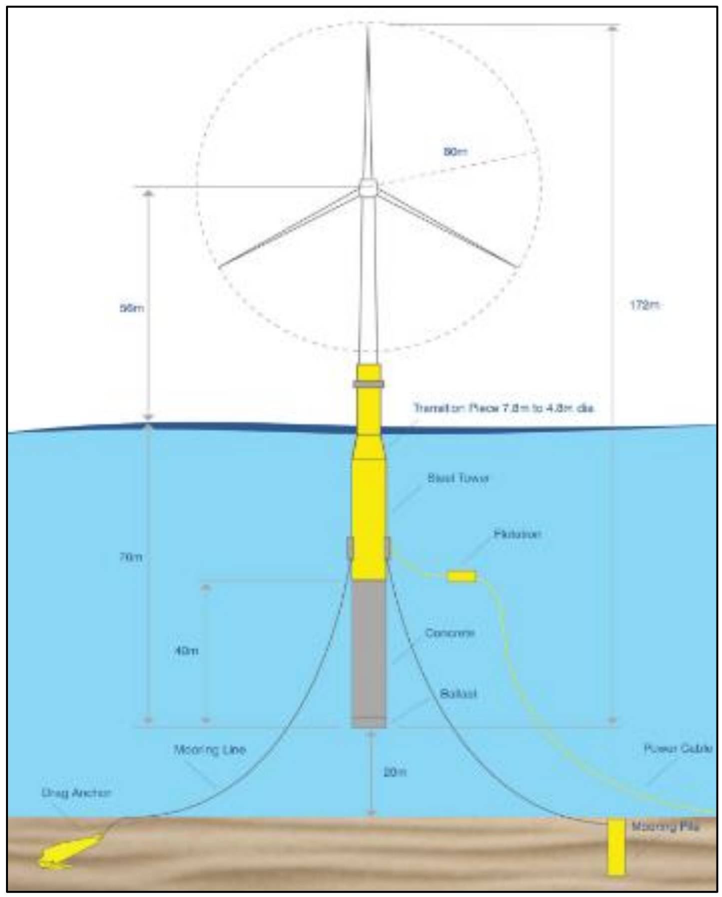


Figure 2 FOWT Design Concept - Toda Hybrid Spar

3.4.3 Advance Spar (Fukushima Hamakaze)

The advance spar (Fukushima Hamakaze) was designed by Japan Marine United Corporation (JMU) to be optimized for construction and transport. The floating structure consists of upper and lower hexagon shaped hulls 51 meters in width connected by a cylindrical spar with an overall draft of 33 meters. The FOWT is using a six-chain catenary system.

- **Designer:** JMU
- **Type**: Spar
- **Hull Material:** Steel
- **Mooring System:** Six-chain spread mooring system
- **Project:** Fukushima FORWARD Phase 2 – 5 MW Capacity (Installed)

Figure 3 FOWT Design Concept - Fukushima Advanced Spar

3.4.4 SeaTwirl

Figure 4 FOWT Design Concept - SeaTwirl

SeaTwirl's substructure consists of a floating element and a keel. As the energy of the wind causes the turbine to rotate, the structure maintains its stability by using the keel and the counter turning moment, similar to the function of a keel on a sailboat.

- **Designer:** SeaTwirl
- **Type**: Spar
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Projects:**
  - SeaTwirl S1 – 30kW Capacity (Installed)
  - SeaTwirl S2– 1 MW Capacity (Under development)

3.4.5 Stiesdal TetraSpar

The TetraSpar is designed by Stiesdal with a modularized floating hull made of a triangular truss structure and a triangular stabilizing keel. It has a very shallow draft in port and during towing. A stabilizing keel can be deployed after hook-up to the mooring.

- **Designer:** Stiesdal
- **Type**: Spar
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Project:** Tetraspar Demo – 3.6 MW Capacity (Under development)

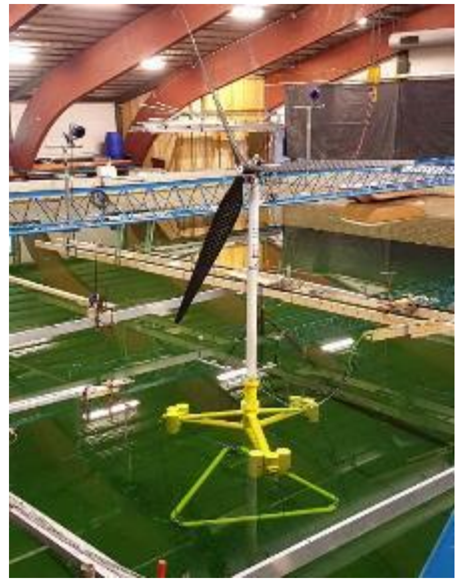


Figure 5 FOWT Design Concept - Stiesdal TetraSpar

3.4.6 WindFloat

Figure 6 FOWT Design Concept - WindFloat

WindFloat consists of three columns, heave plates at the base of each column, and a wind turbine situated on one of the three columns. The innovative features of the WindFloat dampen wave and turbine induced motion, enabling wind turbines to be sited in water depth exceeds 40 meters.

- **Designer:** Principle Power
- **Type**: Semi-submersible
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Projects:**
    - WindFloat 1 (WF1) – 2 MW Capacity (Installed)
    - WindFloat Atlantic (WFA) – 25 MW Capacity (Installed)
    - Kincardine – 50 MW Capacity (Under construction)
    - Golfe du Lion (EFGL) – 30 MW Capacity (Under development)
    - RedWood Coast – 100-500 MW Capacity (Under development)
    - Progression South – 400 MW Capacity (Under development)
    - AWH Oahu Northwest – 400 MW Capacity (Under development)
    - AWH Oahu South – 400 MW Capacity (Under development)
    - KFWind – 500 MW Capacity (Under development)

3.4.7 Fukushima Compact Semi-submersible

Figure 7 FOWT Design Concept – Fukushima Compact Semi-submersible

The compact semi-submersible (Fukushima Mira) was designed by Mitsui Engineering & Shipbuilding Co., Ltd. (MES). This floater consists of one center column supporting the wind turbine, three side columns, three braces, main deck beams, and pontoon beams.

- **Designer:** MES
- **Type**: Semi-submersible
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Project:** Fukushima FORWARD Phase 1 – 2 MW Capacity (Installed)

3.4.8 Fukushima V-shape Semi-submersible

V-shape Semi-Submersible (Fukushima Shimpuu) was designed by Mitsubishi Heavy Industries, Ltd (MHI). The hull consists of a V-shape pontoon and three columns with a depth of 32 meters and a draft of 17 meters. The turbine is mounted on the middle column.

- **Designer:** MHI
- **Type**: Semi-submersible
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Project:** Fukushima FORWARD Phase 2 – 7 MW Capacity (Installed)

Figure 8 FOWT Design Concept – Fukushima V-shape Semi-submersible

3.4.9 VolturnUS

Figure 9 FOWT Design Concept – VolturnUS

VolturnUS, the floating concrete semi-submersible hull is designed by the University of Maine. The hull consists of three outer columns and one center column with the wind turbine on the center column. VolturnUS floating concrete hull technology can support wind turbines in water depths of 45 meters or more.

- **Designer:** University of Maine
- **Type**: Semi-submersible
- **Hull Material:** Concrete
- **Mooring System:** Spread mooring system
- **Projects:**
  - VolturnUS 1:8 – 0.02 Mw Capacity (Installed)
  - New England Aqua Ventus I – 12 MW Capacity (Under development)

3.4.10 Sea Reed

The Sea Reed is designed by Naval Energies. The semi-submersible floating hull is constructed using concrete, steel, or a steel/concrete hybrid combination.

- **Designer:** Naval Energies
- **Type**: Semi-submersible
- **Hull Material:** Steel, concrete, or hybrid
- **Mooring System:** Spread mooring system
- **Project:** Groix & Belle-Ile – 28.5 MW Capacity (Under development)

Figure 10 FOWT Design Concept – Sea Reed

3.4.11 Cobra Semi-Spar

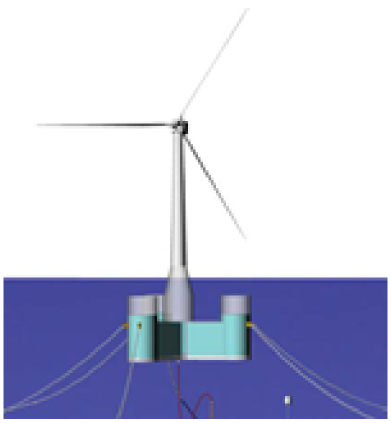


Figure 11 FOWT Design Concept – Cobra Semi-spar

The cobra semi-spar consists of a central cylinder, which provides structural continuity to the tower, and three outer cylinders that provide metacentric stability and buoyancy during transport and operation.

- **Designer:** Cobra
- **Type**: Semi-submersible
- **Hull Material:** Concrete
- **Mooring System:** Spread mooring system
- **Project:** FLOCAN5– 25 MW Capacity (Under development)

3.4.12 OO-Star

Figure 12 FOWT Design Concept – OO-Star

The OO-Star is a semi-submersible floating concrete structure developed within the LIFES50+ project funded by European Commission's Horizon 2020 program.

- **Designer:** Iberdrola
- **Type**: Semi-submersible
- **Hull Material:** Concrete
- **Mooring System:** Spread mooring system
- **Project:** Flagship Demo – 10 MW Capacity (Under development)

3.4.13 Hexafloat

The Hexafloat is a semi-submersible floating structure made of welded steel tubes containing water ballast tanks. A counterweight can be lowered to stabilize heavier loads.

- **Designer:** Saipem
- **Type**: Semi-submersible
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Project:** AFLOWT – 6 MW Capacity (Under development)

Figure 13 FOWT Design Concept – Hexafloat

3.4.14 Eolink

Figure 14 FOWT Design Concept – Eolink

The Eolink is a semi-submersible floating structure with a single point mooring. A set of profiled arms supports the structure, instead of a conventional single tower.

- **Designer:** Eolink
- **Type**: Semi-submersible
- **Hull Material:** Steel
- **Mooring System:** Single point mooring
- **Project:** Eolink Demonstrator – 5 MW Capacity (Under development)

3.4.15 SCD Nezzy

SCD Nezzy has a concrete floating body wind a downwind turbine. The turbine and floating body are combined to form one unit.

- **Designer:** SCD Technology
- **Type**: Semi-submersible
- **Hull Material:** Concrete
- **Mooring System:** Single point mooring
- **Project:** Nezzy Demonstrator – 6 MW Capacity (Under development)

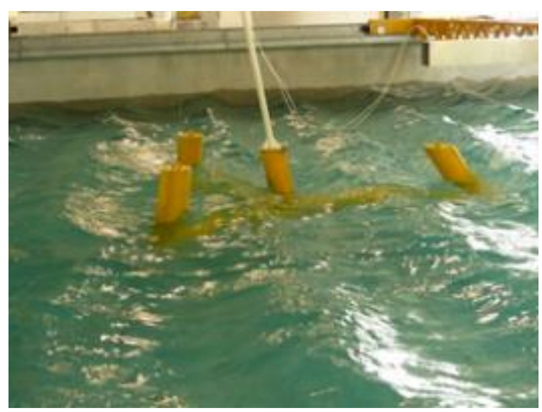


Figure 15 FOWT Design Concept – SCD Nezzy

3.4.16 Nautilus

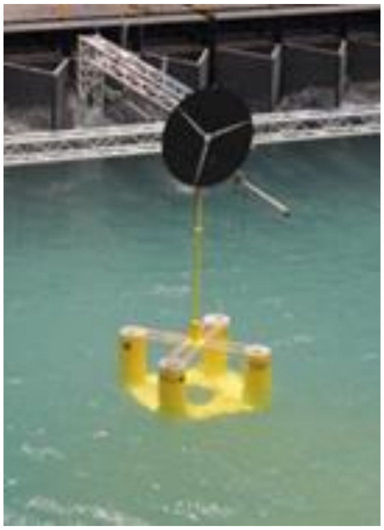


Figure 16 FOWT Design Concept – Nautilus

Nautilus steel semi-submersible is developed within the LIFES50+ project funded by EU Horizon 2020 (H2020) program.

- **Designer:** NAUTILUS Floating Solutions
- **Type**: Semi-submersible
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Project:** N/A

3.4.17 Tri-Floater

The GustoMSC Tri-Floater, characterized by a three column, slender, robust, and brace-less hull, is a semi-submersible floating foundation for all types of offshore wind turbines.

- **Designer:** GustoMSC
- **Type**: Semi-submersible
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Project:** N/A

Figure 17 FOWT Design Concept – Tri-Floater

3.4.18 TrussFloat

Figure 18 FOWT Design Concept – TrussFloat

TrussFloat is a steel semi-submersible floating structure with a centered turbine.

- **Designer:** Dolfines
- **Type**: Semi-submersible
- **Hull Material:** Steel
- **Mooring System:** Spread mooring system
- **Project:** N/A

3.4.19 Ideol Damping Pool

The hull is a square ring-shaped foundation with a patented central opening system (Damping Pool). The shallow draft hull is applicable to deep offshore waters and starting at depths as shallow as 30 meters.

- **Designer:** Ideol
- **Type**: Barge
- **Hull Material:** Concrete or steel
- **Mooring System:** Spread mooring system
- **Project:**
    - Floatgen – 2 MW Capacity (Installed)
    - Hibiki – 3 MW Capacity (Installed)
    - EolMed – 25 MW Capacity (Under development)
    - Atlantis Ideol – 100 MW Capacity (Under development)
    - Acacia – MW N/A

Figure 19 FOWT Design Concept – Ideol Damping Pool

3.4.20 Saitec SATH (Swinging Around Twin Hull)

Figure 20 FOWT Design Concept – Saitec SATH (Swinging Around Twin Hull)

SATH Technology (Swinging Around Twin Hull) is based on a twin hull made of modularly prefabricated and subsequently braced concrete elements. The hull can align itself around a single point of mooring according to the wind and wave direction. The shallow draft hull is suitable for both shallow and deep water.

- **Designer:** Saitec
- **Type**: Barge
- **Hull Material:** Concrete
- **Mooring System:** Single point mooring
- **Projects:**
    - BlueSATH – 0.03 MW Capacity (Installed)
    - DemoSATH – 2 MW Capacity (Under development)
    - CADEMO – 24 MW Capacity (Under development)

3.4.21 SBM TLP

The SBM TLP is a modularized design that requires no construction or port infrastructure. With the tension legs anchored to the seabed, the floater has a reduced seabed footprint.

- **Designer:** SBM Offshore
- **Type**: Tension Leg Platform (TLP)
- **Hull Material:** Steel
- **Mooring System:** Tension leg system
- **Projects:**
  - Provence Grand Large (PGL) – 25 24 MW Capacity (Under development)
  - CADEMO – 24 MW Capacity (Under development)

Figure 21 WT Design Concept – SBM TLP

3.4.22 Pivotbuoy TLP

Figure 22 FOWT Design Concept – PivotBuoy TLP

PivotBuoy design is based on Tension-Leg Platforms (TLP) technology. It uses a single point mooring system and a downwind configuration to allow the platform to weathervane.

- **Designer:** X1 Wind
- **Type**: Tension Leg Platform (TLP)
- **Hull Material:** Steel
- **Mooring System:** Tension leg system, single point
- **Project:** PivotBuoy 1:3 Scale – 0.2 MW Capacity (Under construction)

3.4.23 Gicon TLP

Gicon design is based on Tension-Leg Platforms (TLP) technology attached to the seabed with taut mooring lines.

- **Designer:** Gicon
- **Type**: Tension Leg Platform (TLP)
- **Hull Material:** Concrete
- **Mooring System:** Tension leg system
- **Project:** Gicon SOF **–** 2.3 MW Capacity (Under development)

Figure 23 FOWT Design Concept – Gicon TLP

3.4.24 Pelastar TLP

Figure 24 FOWT Design Concept – Pelastar TLP

Pelastar TLP design is based on Tension-Leg Platforms (TLP) technology. It utilizes tendons manufactured from high-performance materials.

- **Designer:** Glosten
- **Type**: Tension Leg Platform (TLP)
- **Hull Material:** Steel
- **Mooring System:** Tendon system using synthetic fiber cables
- **Project:** N/A

3.4.25 TLPwind TLP

TLPWind design is based on Tension-Leg Platforms (TLP) technology. The concept is developed within the LIFES50+ project funded by European Commission's Horizon 2020 program.

- **Designer:** Iberdrola
- **Type**: Tension Leg Platform (TLP)
- **Hull Material:** Steel
- **Mooring System:** Tension leg system
- **Project:** TLPWind UK – 5 MW Capacity (Under development)

Figure 25 FOWT Design Concept – TLPWind TLP

3.4.26 Hexicon Multi-Turbine Semi-Submersible

The Hexicon multi-turbine platform is based on a semi-submersible design with three columns connected with a truss structure. The turret mooring system allows the platform to weathervane.

- **Designer:** Hexicon
- **Type**: Multi-turbine platform
- **Hull Material:** Steel
- **Mooring System:** Multi-turbine platform
- **Projects:**

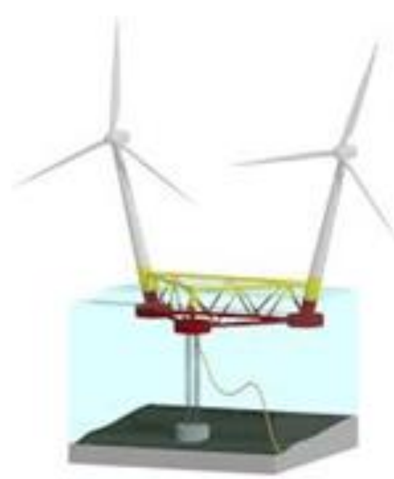


Figure 26 FOWT Design Concept – Hexicon Multi-turbine Semi-submersible

- Hexicon Dounreay Trì project – 10 MW Capacity (Under development)
- Donghae TwinWind – 200 MW Capacity (Under development)
- WunderHexicon – MW Capacity N/A (Under development)

3.4.27 W2power

The W2Power is based on a semi-submersible design. The single mooring system allows the platform to weathervane.

- **Designer:** EnerOcean
- **Type**: Multi-turbine platform
- **Hull Material:** Steel
- **Mooring System:** Single point mooring
- **Project:** W2Power 1:6 Scale **–** 0.2 MW Capacity (Installed)

Figure 27 FOWT Design Concept – W2Power

3.4.28 Floating Power Plant

Figure 28 FOWT Design Concept - Floating Power Plant

This platform is a hybrid wind-wave power plant. The single mooring system allows the platform to weathervane.

- **Designer:** Floating
- **Type**: Multi-turbine platform
- **Hull Material:** Steel
- **Mooring System:** Single point mooring
- **Project:** Poseidon 37 Demonstrator – 0.033 MW Capacity (Installed)

3.5 FOWT RESEARCH

The ongoing FOWT research projects were reviewed by the ABSG team to gather information on technical, environmental, and economic issues related to FOWT.

Based on the review, the following information is summarized in this section on FOWT research:

- Organizations involved in FOWT research
- FOWTs research programs
- FOWTs open sea test facilities
- FOWTs ongoing research projects

3.5.1 Organizations Involved in FOWT Research

Table 6 includes a list of organizations currently involved in floating offshore wind activities, including promotion, research, and standards and regulatory development.

Table 6 Organizations

Country /Region	Organization	Organization Type	Website
US	US Department of Energy (DOE)	Government	https://www.energy.gov/
US	Bureau of Ocean Energy Management (BOEM)	Government, Regulation	https://www.boem.gov/
US	American Wind Energy Association (AWEA)	Research, standard	https://www.awea.org/
US	National Renewable Energy Laboratory (NREL)	Research	https://www.nrel.gov/
US	Sandia National Laboratory (SNL)	Research	https://www.sandia.gov/
US	New York State Energy Research and Development Authority (NYSERDA)	Government	https://www.nyserda.ny.gov/
Europe	European Union (EU)	Government	https://europa.eu/european-union/index_en
Europe	WindEurope (former EWEA)	Research	https://windeurope.org/
UK	The Crown Estate	Government	https://www.thecrownestate.co.uk/
UK	Offshore Renewable Energy (ORE) Catapult	Research	https://ore.catapult.org.uk/
UK	Carbon Trust	Research	https://www.carbontrust.com/
UK	Deepwind Offshore Wind Cluster	Supply Chain Development	https://www.offshorewindscotland.org.uk/deepwind-cluster/
Japan	Japan Wind Power Association (JWPA)	Research	http://jwpa.jp/index_e.html
Global	Global Wind Energy Council (GWEC)	Research	https://gwec.net/
Global	International Energy Agency (IEA)	Research	https://www.iea.org/
Global	International Electrotechnical Commission (IEC)	Research, Standard	https://www.iec.ch/
Global	International Renewable Energy Agency (IRENA)	Research	https://www.irena.org/

3.5.2 FOWTs Research Programs

Research programs, which resulted in subsequent published technical reports and papers related to FOWTs, are summarized in Table 7. Relevant technical reports and papers from these research programs on FOWTs are further reviewed and summarized in Section 4 for the purpose of technological assessment.

Table 7 FOWTs Research Programs (Since 2000)

Year	Research Program	Manager
2009-	Various Research Programs in science, technology, education and mathematics (STEM)	National Science Foundation (NSF)
2010-2013	DeepCwind Consortium Research Program	University of Maine

Year	Research Program	Manager
2010-2014	Light Rotor 10-MW Reference Wind Turbine	Technical University of Denmark (DTU)
2011-	Technology Assessment Program (TAP) (Renewable Energy)	Bureau of Safety and Environmental Enforcement (BSEE) /Bureau of Ocean Energy Management (BOEM)
2012-	Offshore Wind Accelerator	Carbon Trust
2014-2020	Horizon 2020 Program (H2020)	European Union (EU)
2016-	Floating Wind Joint Industry Project (JIP)	Carbon Trust
2016-	MassCEC Metocean Data Initiative	Massachusetts Clean Energy Center (MassCEC)
2017	New York State Offshore Wind Master Plan	New York State Energy Research and Development Authority (NYSERDA)
2017	LiDAR Buoy Loan Program	Pacific Northwest National Laboratory (PNNL)
2017-	Research & Innovation Strategic Programmes	Offshore Renewable Energy (ORE) Catapult
2018-	National Offshore Wind Research and Development Consortium (NOWRDC)	New York State Energy Research and Development Authority (NYSERDA)
2018	Advanced Next-Generation, High-Efficiency, Lightweight Wind Turbine Generator	Department of Energy (DOE)
2018	Advanced Wind R&D to Reduce Costs and Environmental Impacts	Department of Energy (DOE)
2019	Small Business Innovation Research Phase I Release 2	Department of Energy (DOE)
2019	Wind Energy Research, Development, and Demonstration	Department of Energy (DOE)
2019-2022	Wind Administrated Research Task 30 OC6	International Energy Agency (IEA)
2020	Advance to Next-Generation Wind Energy Technology (Next Wind)	California Energy Commission (CEC)
2020	ATLANTIS Program	Department of Energy DOE ARPA-e

The National Science Foundation (NSF) provides research grants for floating offshore turbine design, including composite foundations, anchor and mooring design, and simulation and modeling tools. Table 8 provides a summary of NSF research.

Table 8 NSF Research

Year	Project	Investigator
2009-2012	Commercialization of Advanced Composites in Offshore Wind Energy	University of Maine
2011-2015	Simulation Based Design for Deep Water Offshore Wind Turbines Including Wave Loads and Motions	Tuskegee University
2011-2016	Floating Offshore Wind Turbines: Conceptual Assessment of Highly Compliant Platforms using Theory, Design and Simulation	Texas A&M University
2015-2018	REU site: Offshore wind energy: Solving the Engineering, Environmental & Socio-Economic Challenges	University of Massachusetts Amherst
2015-2020	Efficient Multiline Mooring Systems for Floating Wind Turbines	Texas A&M University

Year	Project	Investigator
2017-2021	Uncertainty Modeling, Probabilistic Models, and Life-cycle Reliability of Floating Offshore Wind Turbines	Prairie View A&M University
2018-2021	Advanced Control Strategies for Floating Offshore Wind Farms	University of Maine
2020-2023	Novel and Efficient Seabed Ring Anchor for Omnidirectional Loading	University of California-Davis

The DeepCwind Consortium is led by the University of Maine and consists of approximately 30 members around the country, including two universities, two nonprofits, and a diverse group of industry leaders. The University of Maine-led consortium developed the floating concrete hull design VolturnUS.

Light Rotor project, led by the Technical University of Denmark (DTU), developed the so-called Light Rotor 10-MW Reference Wind Turbine (LR10- MW RWT).

For the BSEE TAP program, the technical reports on FOWTs and related topics are summarized in references (ABS, 2012; ABS,2013; Malcolm Sharples, 2011; Maine Marine Composites, LLC, 2015; Moffat & Nichole, Inc, 2015; and PMSS America, Inc, 2014).

The Offshore Wind Accelerator (OWA) program managed by Carbon Trust aims to reduce the cost of offshore wind, overcome market barriers, develop industry best practices, and trigger the development of new industry standards.

MassCEC Metocean Data Initiative is to enable public access to quality-assured metocean data in the area located in Massachusetts in state waters one mile south of Martha's Vineyard to collect wind data near federal offshore wind energy areas (WEAs).

The New York State Offshore Wind Master Plan (Master Plan), led by NYSERDA, is a comprehensive roadmap and suite of more than 20 studies for the first 2,400 megawatts of offshore wind energy that encourages the development of offshore wind in a manner that is sensitive to environmental, maritime, economic, and social issues while addressing market barriers and aiming to lower costs.

LiDAR Buoy Loan Program implemented by the DOE's Wind Energy Technologies Office is to lend the meteorological and oceanographic data buoys owned by DOE to qualified parties to acquire wind resource characterization data in areas of interest for offshore wind energy development. PNNL manages the loan program.

The Department of Energy Wind Energy Technologies Office invests in energy science research and development activities that enable the innovations needed to advance U.S. wind systems, reduce the cost of electricity, and accelerate the deployment of wind power. Among the more than 250 Wind Research & Development Projects, the recent projects that are related to FOWTs are listed in Table 7.

Advance to Next-Generation Wind Energy Technology (Next Wind) is to facilitate the development of next-generation wind energy technologies and result in increased competitiveness, performance, and reliability, while lowering the cost and the environmental and wildlife impacts of wind energy.

The Offshore Renewable Energy Catapult is the UK's leading technology innovation and research center for offshore wind, wave, and tidal energy. Research & Innovation Strategic Programmes address the latest research and disruptive technology for the offshore renewable energy sector.

The Offshore Code Comparison, Collaboration, Continued, with Correlation and unCertainty (OC6) is an international research project operating under the International Energy Agency (IEA) Wind Task 30. The project is focused on validating the tools used to design offshore wind systems. OC6 implements a three-way validation process where both the engineering-level modeling tools and higher-fidelity tools are compared to measurement data. The results will be used to help inform the improvement of engineering-level models, and/or guide the development of future test campaigns.

The OC6 project consists of four phases to be performed over four years (2019-2023) (DOE, n.d.), as given in Table 9.

Table 9 OC6 Project Phases

#	OC6 PHASE
Phase Ia	Validate the nonlinear hydrodynamic loading on floating offshore wind support structures
Phase Ib	Additional data focused on Phase I from a component-level validation campaign geared towards CFD validation
Phase II	Develop and verify an advanced soil/structure interaction model for representing the pile/foundation interaction
Phase III	Validate the aerodynamic loading on a wind turbine rotor undergoing large motion caused by a floating support structure
Phase IV	Benchmark and validate methods for combining potential flow and viscous hydrodynamic load models for novel FOWTs support structures

The Carbon Trust's Floating Wind Joint Industry Project (JIP) is a collaborative research and development (R&D) initiative that aims to investigate the challenges and opportunities for the deployment of large-scale commercial floating wind farms (Carbon Trust, n.d.; Carbon Trust, 2018; Carbon Trust, 2020).

Table 10 Carbon Trust Floating Wind Joint Industry Project Phases

#	FLOATING WIND JIP PHASE	STATUS
Phase I (2017)	Electrical systems	Complete (see Carbon Trust 2018)
	Mooring systems	
	Infrastructure and logistics	
Phase II (2018-2019)	Turbine requirement and foundation scaling	Complete (see Carbon Trust 2020)
	Heavy lift offshore operations	
	Dynamic export cable development	
	Monitoring and inspection	
Phase III	Moorings in challenging environments	Ongoing

#	FLOATING WIND JIP PHASE	STATUS
(2019-2020)	Heavy lift maintenance	
	Tow to port maintenance	
	Floating Wind Technology Acceleration Competition	
Phase IV (2020-)	Assessment of Wind Turbine Generators for floating wind farms	Ongoing
	Floating Wind Access and Availability	
	Floating Wind Yield	
	Numerical Modeling Guidelines and Standards for Floating Wind	

Horizon 2020 Program (H2020) is the EU's funding program for research and innovation, with nearly €80 billion of funding available over seven years (2014 to 2020). Horizon 2020 couples research and innovation and has an emphasis on excellent science, industrial leadership, and tackling societal challenges. The goal is to ensure Europe produces world-class science, removes barriers to innovation, and makes it easier for the public and private sectors to work together in delivering innovation. A project list for the H2020 program is given in Table 11.

Table 11 H2020 FOWTs Projects

Year	Project
2010	High Power, high Reliability offshore wind technology (HiPRwind)
2015	Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50 meters (LIFES50+)
2016	New Floating Platform for offshore wind in deep waters (FLOW)
2017	Towards Game-changer Service Operation Vessels for Offshore Windfarms (NEXUS)
2018	Leading the floating wind market development (LEADFLOAT)
2019	PivotBuoy - An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind
2019	Cost Reduction and increase performance of floating WIND technology (COREWIND)
2019	Floating Wind Energy network (FLOAWER)
2019	Innovative, low cost, low weight and safe floating wind technology optimized for deep water wind sites (FLOTANT)
2019	European Technology and Innovation Platform on Wind Energy (ETIPWind)- Aligning Wind Energy Research and Innovation Strategies
2020	novel design, production and operation approaches for floating WIND turbine farms (STEP4WIND)

The National Offshore Wind Research and Development Consortium is a nationally focused, not-for-profit organization collaborating with industry on prioritized R&D activities to reduce the levelized cost of energy (LCOE) of offshore wind in the U.S. while maximizing other economic and social benefits. The National Offshore Wind Research and Development Consortium (NOWRDC) projects and related technical challenges are given in Table 12 (NOWRDC, 2020).

Table 12 NOWRDC FOWTs Projects (NOWRDC, 2020)

Pillar	Technical Challenge Area	Project	Investigator
Pillar 1: Offshore Wind Plant Technology Advancement	1.1: Array Performance and Control Optimization	N/A	N/A
	1.2: Cost-Reducing Turbine Support Structures for U.S. Markets	N/A	N/A
	1.3: Floating Structure Mooring Concepts for Shallow and Deep Waters	Demonstration of Shallow-Water Mooring Components for FOWTs (ShallowFloat)	Principle Power, Inc.
		Design and Certification of Taut-synthetic Moorings for Floating Wind Turbines	University of Maine
		Dual-Functional Tuned Inverter Damper for Enhanced Semi-Sub Offshore Wind Turbine	Virginia Tech University
		Innovative Anchoring System for FOWTs	Triton Systems, Inc
		Techno-Economic Mooring Configuration and Design for FOWTs	University of Massachusetts Amherst
	1.4: Power System Design and Innovation Challenge Statement	Development of Advanced Methods for Evaluating Grid Stability Impacts	National Renewable Energy Laboratory
Pillar 2: Offshore Wind Power Resource and Physical Site Characterization	2.1: Comprehensive Wind Resource Assessment	N/A	N/A
	2.2: Development of a Metocean Reference Site	Development of a Metocean Reference Site near the Massachusetts and Rhode Island Wind Energy Areas	Woods Hole Oceanographic Institute
Pillar 3: Installation, Operations and Maintenance, and Supply Chain	3.2: Offshore Wind Digitization through Advanced Analytics	Enabling Condition Based Maintenance for Offshore Wind	General Electric
		Physics Based Digital Twins for Optimal Asset Management	Tufts University
		Radar Based Wake Optimization of Offshore Wind Farms	General Electric
		Survival Modeling for Offshore Wind Prognostics	Tagup, Inc.
	3.3: Technology Solutions to Accelerate U.S. Supply Chain	20GW by 2035: Supply Chain Roadmap for Offshore Wind in the U.S.	National Renewable Energy Laboratory

The ATLANTIS program (DOE, 2019a) seeks to develop new technical pathways to design economically competitive FOWTs. The program urges the application of Control Co-Design (CCD) methodologies that (1) bring together engineering disciplines to work concurrently, as opposed to sequentially, and (2) consider control engineering principles from the start of the design process. By analyzing the numerous subsystem dynamic interactions that comprise the FOWTs, CCD methodologies can propose control solutions that enable optimal FOWT designs that are not achievable otherwise. Design optimization is defined here as the maximization of the specific swept-rotor-area per unit of total-mass (m^2/kg) of the FOWT for a given power generation efficiency.

Projects in this program will cover three fundamental areas:

1. **New Design:** radically new FOWT designs with significantly lower mass/area.
2. **New Computer Tools**: a new generation of computer tools to facilitate control co-design of the FOWTs.
3. **Experimental Data:** generation of real-data from full and lab-scale experiments to validate the FOWT designs and computer tools.

The radically new FOWT designs include:

- Floating platforms
- Turbine rotors
- Towers, mooring, and anchor systems
- Generators and drivetrains
- Materials, manufacturing, and installation methods
- Sensors, actuators, and control paradigms

Instead of the classical design method, where each engineering team (mechanical, electrical, electronics, control, etc.) is an independent step in a sequential process (see Figure 29 (Left)), Control Co-Design (CCD), also known as Integrated Control or just Co-Design, brings together various technical disciplines to work concurrently from the start (see Figure 29 (Right)).

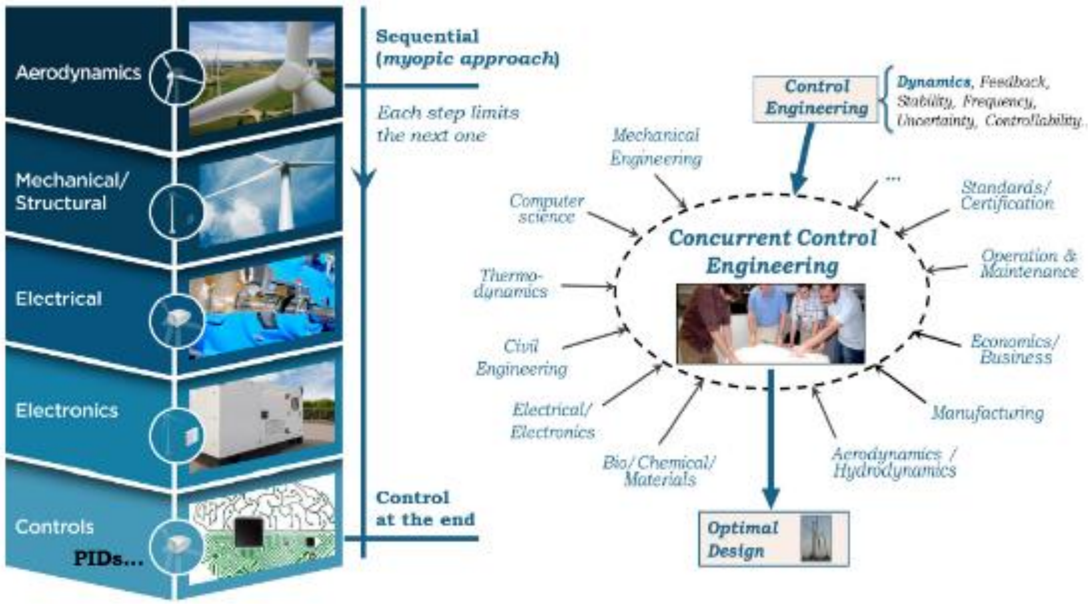


Figure 29 (Left) Classical sequential design process vs. (Right) Control Co-Design (DOE, 2018a.)

Table 13 provides a list of FOWT projects under the ATLANTIS program (DOE, n.d.).

Table 13 ATLANTIS FOWTs Projects (DOE, n.d.)

Year	Project	Investigator
2020	ARCUS Vertical-Access Wind Turbine	Sandia National Laboratories
2020	Design and Develop Optimized Controls for a Lightweight 12 MW Wind Turbine on an Actuated Tension Leg Platform	General Electric Company
2020	DIGIFLOAT: Development, Experimental Validation and Operation of a Digital Twin Model for Full-scale Floating Wind Turbines	Principal Power Inc.
2020	A Low-Cost Floating Offshore Vertical Axis Wind System	The University of Texas at Dallas
2020	A Co-Simulation Platform for Off-Shore Wind Turbine Simulations	The University of Massachusetts
2020	USFLOWT: Ultraflexible Smart FOWT	National Renewable Energy Laboratory
2020	Wind Energy with Integrated Servocontrol (WEIS): A Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems	National Renewable Energy Laboratory
2020	The FOCAL Experimental Program	National Renewable Energy Laboratory
2020	AIKIDO - Advanced Inertial and Kinetic energy recovery through Intelligent (co)-Design Optimization	Other lab – San Francisco
2020	Scale Model Experiments for Co-Designed FOWTs Supporting a High-Capacity (15MW) Turbine	WS Atkins – Houston

Year	Project	Investigator
2020	Computationally Efficient Atmospheric-Data-Driven Control Co-Design Optimization Framework with Mixed-Fidelity Fluid and Structure Analysis	Rutgers University
2020	Model-Based Systems Engineering and Control Co-Design of FOWTs	The University of Central Florida
2020	Ultra-light Concrete FOWT with NASA-developed Response Mitigation Technology	The University of Maine

3.5.3 FOWTs Open Sea Test Facilities

Based on the literature review, the open sea test facilities that have demonstration FOWTs installed are summarized in Table 14.

Table 14 FOWTs – Open Sea Test Facilities

Country	Test Facilities	Location	Capacity	Projects
US	UMaine Deepwater Offshore Wind Test Site	Offshore Monhegan Island in the Gulf of Maine, US	25 MW	New England Aqua Ventus I
France	Ecole Centrale de Nantes (SEM-REV)	Offshore Le Croisic, France	8 MW	Floatgen Eolink Demonstrator
Ireland	Atlantic Marine Energy Test Site (AMETS)	Offshore the Irish west coast, Ireland	10 MW	AFLOWT
Norway	Marine Energy Test Centre (Metcentre)	Offshore Karmøy, Norway	10 MW	Hywind Demo (Zefyros) TetraSpar Demo Flagship Demo
Spain	Biscay Marine Energy Platform (BIMEP)	Offshore Basque, Spain	20 MW	DemoSATH
Spain	Oceanic Platform of the Canary Islands (PLOCAN)	Offshore Gran Canaria, Spain	10 MW	W2Power 1:6 Scale PivotBuoy 1:3 Scale

3.5.4 Summary of Ongoing FOWT Research Projects

A full summary of all the FOWT research projects discussed throughout Section 3.5 can be found in Appendix C. In the Appendix, there are two tables. The first table sorts the research projects by the year the project began, provides a consolidated list of ongoing research projects detailing the year, project, description, investigator, and the administrator. The second table provides a summary of the ongoing FOWT research projects grouped by the category of technical challenges, including turbines, floating substructures, mooring and anchors, electrical infrastructure, construction (manufacturing, transportation, and installation), operation and maintenance, site conditions, design analysis tool and validation, and design guidelines and standards.

3.6 CURRENT STANDARDS AND GUIDELINES

The organizations involved in the development of standards for FOWTs are:

- ABS (American Bureau of Shipping)
- IEC (International Electrotechnical Commission)
- DNV GL (Det Norske Veritas Germanischer Lloyd)
- BV (Bureau Veritas)
- LR (Lloyd's Register)

Additionally, the AWEA (American Wind Energy Association) /ANSI (American National Standards Institute) U.S. offshore wind standards initiative began in September 2017 (Musial et al., 2020). The AWEA Wind Standards Committee formed an offshore wind subcommittee to oversee the development of five working groups to address deficiencies in the current state of U.S. offshore wind standards. This new standard of recommended practices will (1) help clarify design requirements for developers and (2) enable BOEM/BSEE to create regulations that better reflect industry best practices, but publication is not expected until late 2021. Currently, there is insufficient guidance in the public domain to establish best practices for U.S. offshore projects.

The currently available guidelines available are listed below.

ABS Guides and Guidance Notes

- ABS Guide for Building and Classing Floating Offshore Wind Turbines, July 2020
- ABS Guidance Notes on Global Performance Analysis for Floating Offshore Wind Turbines, July 2020

AWEA

- AWEA Offshore Compliance Recommended Practices (AWEA OCRP 2012)

IEC Standards

- IEC 61400-1, Wind Energy Generation Systems – Part 1: Design Requirements, 4th Edition, 2019
- IEC 61400-3-1, Wind Energy Generation Systems – Part 3-1: Design Requirements for Fixed Offshore Wind Turbines, 1st Edition, 2019
- IEC TS 61400-3-2 (Technical Specification), Wind Energy Generation Systems – Part 3-2: Design Requirements for Floating Offshore Wind Turbines, 1st Edition, 2019
- IECRE OD-501 (Operational Document), IEC System for Certification to Standards relating to Equipment for use in Renewable Energy applications (IECRE System): Type and Component Certification Scheme, 2nd Edition, 2018

- IECRE OD-502 (Operational Document), IEC System for Certification to Standards relating to Equipment for use in Renewable Energy applications (IECRE System): Project Certification Scheme, 1st Edition, 2018

DNV GL Standards

- DNVGL-RP-0286, Coupled Analysis of Floating Wind Turbines, May 2019
- DNVGL-ST-0119, Floating Wind Turbine Structures, July 2018
- DNVGL-ST-0437, Loads and Site Conditions for Wind Turbines, November 2016

BV Guidance Notes

- BV Guidance Note NI572, Classification and Certification of Floating Offshore Wind Turbines, January 2019

LR Guidance Notes

- LR Guidance Notes for Offshore Wind Farm Project Certification, July 2019

The review of standards on electrical system is summarized in Section 4.3.4.

4 TECHNOLOGICAL ASSESSMENT

The FOWT technical assessment is based on the literature review of publicly available information on FOWT projects; ongoing FOWT research projects; and FOWT research, standards development, and certification. The technological assessment reviews the following factors:

- Structural design and dynamic modeling
- Mooring and anchorage designs
- Dynamic power cable system
- Fabrication and installation methods
- Available Facilities in the U.S.
- Current modeling efforts

4.1 STRUCTURAL DESIGN AND DYNAMIC MODELING

Based on the assessment, the technological issues for the structural design and dynamic modeling are identified in the following areas:

- Design optimization
- Material (concrete, steel)
- Design considerations for fabrication and installation
- Design analysis methodology, such as integrated design

4.1.1 Design Optimization

4.1.1.1 Project Experiences

Hywind and WindFloat concepts are designed from prototypes with a small turbine to pre-commercial wind farms with large wind turbines, allowing for design optimization of the floating substructure. For both the Hywind and WindFloat concepts, the scale-up optimized designs and reduced cost.

When scaling up a FOWT, the increase in floating substructure and mooring system sizes are less than the increase in turbine power. The weight of a floating substructure is reduced per MW when floating substructures are scaled up to larger wind turbines. Similarly, the weight of the mooring system and the power cable system will also be reduced. Scaling up the floating substructure to large turbines will be more efficient than the floating substructure of smaller turbines and reduce cost per MW.

Design optimization of platform design in terms of platform heel motion is also an important aspect. Tower inclination is induced by platform heel motions. Optimization of platform design can reduce platform heel motions, thus the tower inclination.

For the Hywind concepts, the designs of Hywind Scotland to Hywind Tampen are scaled up from the Hywind Demo with optimized design changes. The Hywind Tampen uses a concrete floating substructure. A comparison of the Hywind Demo, Hywind Scotland, and Hywind Tampen projects is provided in Table 15.

Table 15 Comparison of Hywind Projects (Equinor, n.d.; Equinor, 2019)

Design Parameters	Hywind Demo	Hywind Scotland	Hywind Tampen
Year	2009	2017	2022
Power capacity	2.3 MW	30 (5×6) MW	88 (11×8) MW
Location	Offshore Karmøy, Norway	Offshore Peterhead, Scotland, UK	Snorre and Gullfaks offshore fields, offshore Norway
Water depth	220 meters (722 feet)	95-120 meters (312-394 feet)	260-300 meters (853-984 feet)
Distance to shore	10 kilometers (6.2 miles)	25 kilometers (15.5 miles)	140 kilometers (87 miles)
Mass (displacement)	5,300 tons	11,200 tons	Around 22,000 tons
Draught	100 meters	78 meters	90 meters
Hub height	65 meters	98 meters	105 meters
Substructure Diameter	8.3 meters	14.4 meters	18.3 meters
Hull material	Steel	Steel 2,300 tons	Concrete 9,000 tons
Rotor diameter	85 meters	154 meters	167 meters
Anchor	Drag embedded anchor	Suction anchor	Suction anchor (shared)
Mooring	3-line (wire/chain, clump weight)	3-line catenary (chain)	3-line mooring
Inter-array cable	Not applicable	33 kV	66 kV
Export cable	24 kV	33 kV	66 kV

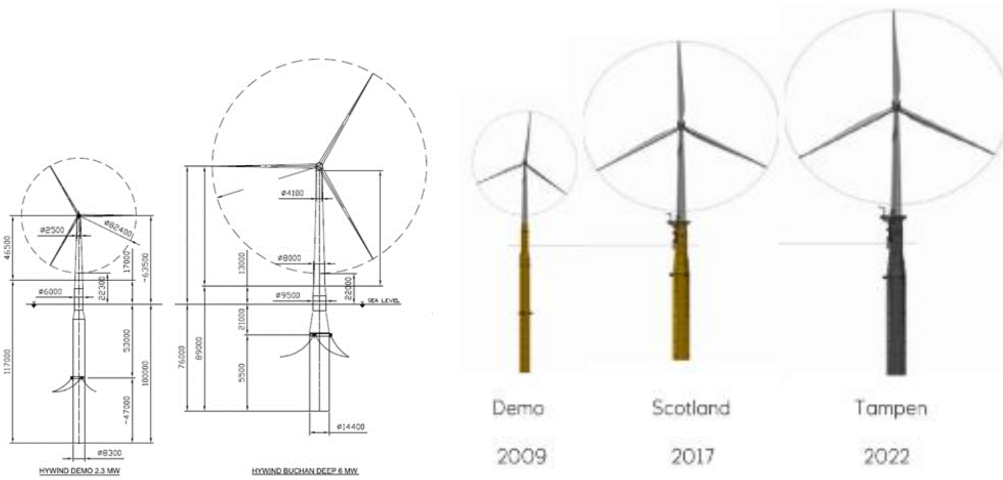


Figure 30 Comparison of Hywind Demo (2.3 MW) to Hywind Scotland (6 MW), and Hywind Tampen (Equinor, 2014; Equinor, 2019)

Roddier et al. (2017) presented five-year performance and lessons learned for the WindFloat 1 (WF1) project. The WF1 prototype was designed for a five-year life and has recently been decommissioned after five years spent offshore. The paper reviewed and concluded the demonstration project's full lifecycle.

As pointed by the authors, the large aerodynamic loads generated by the turbine have a substantial effect on the motion of the substructure. Conversely, motions of the platform generated by waves have a significant impact on the turbine response. Because of the complex responses of both the turbine and the hull, it is extremely difficult to "decouple" the hydrodynamic response from the "aerodynamic" response. A fully coupled simulation tool is the most efficient way to determine how accurately the system responses to achieve an optimized design.

The WindFloat Atlantic (WFA) FOWT was scaled up from the WF1 (see WindPlus, 2019). WindPlus performed scale up and structural optimization for the design (see Figure 31). Scaling-up and additional innovations delivered important savings.

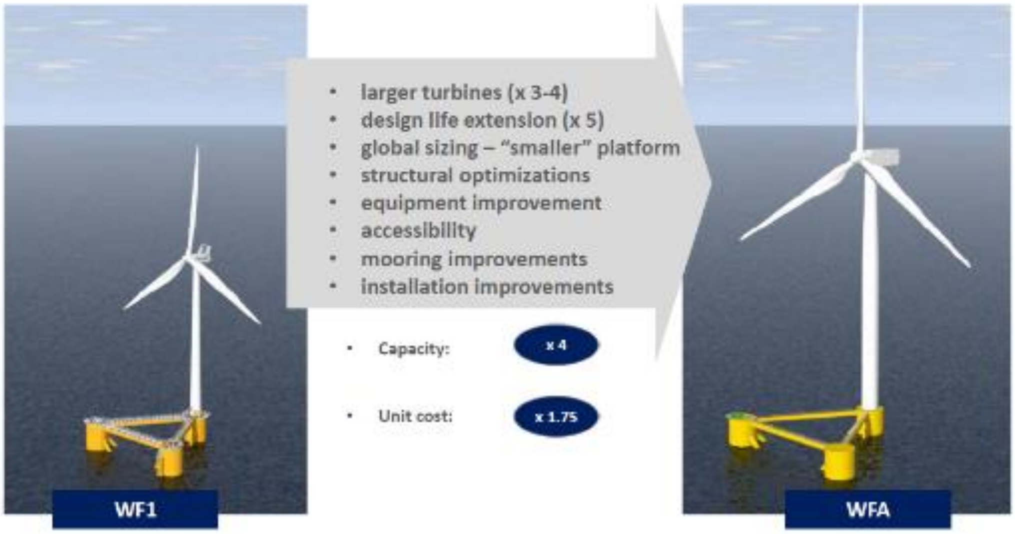


Figure 31 Windfloat Atlantic - Scaling-up and additional innovations (WindPlus, 2019)

A comparison of the WF1 and WFA is provided in Table 16. The next-generation WindFloats will be considerably lighter relative to the 2 MW flagship, as turbine capacity will quadruple to 8 MW, but hull weight only doubles, with a draft of no more than 20 meters (Powerlinks, 2018).

Table 16 Comparison of WF1 and WFA projects (Principle Power, 2014; Roddier et al., 2017; Power-technology, n.d.; Powerlinks, 2018)

Design Parameters	WindFloat 1	WindFloat Atlantic
Year	2011	2020
Power capacity	2 MW	25.2 (3×8.4) MW
Location	Offshore Aguçadoura, Portugal	Offshore Viana do Castelo, Portugal
Water depth	49 meters (161 feet)	85-100 meters (279-328 feet)
Distance to shore	5 kilometers (3.1 miles)	20 kilometers (12.4 miles)
Mass (displacement)	2,800 tons	About double of WF1
Draught	13.7 meters	<20 meters
Hub height	70 meters	108 meters
Substructure Dimension	23.2-meter height, 38 meters column-to-column	30-meter height, 50 meters column-to-column
Hull material	Steel	Steel
Rotor diameter	80 meters	164 meters
Anchor	Drag embedded anchor	Drag embedded anchor
Mooring	4-line mooring system (chain/wire)	3-line mooring system (Dyneema DM20/chain/clump weight)
Inter-array cable	Not applicable	66 kV

Design Parameters	WindFloat 1	WindFloat Atlantic
Export cable	Subsea dynamic cable	150 kV (operated at 66 kV)

4.1.1.2 Linearized Integrated Design Optimization

Hegseth et al. (2020) presented a linearized aero-hydro-servo-elastic FOWT model to perform integrated design optimization of the platform, tower, mooring system, and blade-pitch controller for a 10 MW spar floating wind turbine.

FOWTs are complex multidisciplinary systems, which makes design optimization a challenging and time-consuming task. Different components, such as the wind turbine control system, tower, platform, and mooring system, are typically designed separately in a sequential manner; however, due to strong coupling between the disciplines, this often leads to suboptimal solutions at the overall system level. Therefore, it is desirable to use an integrated optimization approach where the components are designed simultaneously while considering all relevant disciplines. Multidisciplinary design optimization (MDO) techniques can be used to solve such problems.

The current work develops an integrated optimization process that considers the tower and platform design simultaneously and captures the coupling effects between the two subsystems. A flexible hull, combined with distributed hydrodynamic forces, also enables the structural design of the platform to be integrated into the global optimization loop. A computationally efficient low-fidelity model is used to analyze the linearized aero-hydro-servo-elastic dynamics of a 10 MW spar FWT in the frequency domain.

The spar platform, tower, mooring system, and control system are then optimized in an integrated fashion. The results are verified against nonlinear time-domain analyses. The rotor design is not modified during the optimization since the model is considered unsuitable for local blade response. Since the presented design optimization methodology is based on a simplified dynamic model, its main purpose is to help designers in the preliminary design phase.

4.1.1.3 Automated Design Optimization

Leimeister et al. (2020) presented an automated optimization approach applied to a FOWT system in order to design an advanced spar-type floating platform, which is optimized with respect to the change in hydrodynamics and their impact on the main system performance, while structural, manufacturability, or other constraints are not considered.

Three cylindrical sections with individual diameters and heights, as well as the ballast filling height, are the modifiable design variables of the optimization problem. Constraints regarding the geometry, ballast, draft, and system performance are specified. The optimization objective to minimize the floater structural material shall represent the overall goal of cost reduction. Preprocessing system simulations are performed to select a critical design load case, which is used within the iterative optimization algorithm. This itself is executed by employing fully integrated framework for automated simulation and optimization and utilizes a genetic algorithm. The presented design optimization example and approach emphasize the complexity of the optimization problem.

4.1.1.4 Multidisciplinary, Multi-fidelity, Systems Optimization

Barter et al. (2020) pointed out that floating offshore wind plants have the potential to be cost-competitive with fixed-bottom installations. However, because the technology has not yet been deployed at a commercial scale, it is not clear when and with what configurations this potential cost parity can be achieved. The article puts forth a long-term vision for a research program and design methodology that may be able to push floating wind plants toward a lower levelized cost of energy than fixed-bottom offshore wind.

The designs for the first wave of pre-commercial floating wind turbines adapted substructure concepts directly from the offshore oil and gas industry and relied on mature wind turbine designs intended for land-based or fixed-bottom offshore applications. These first floating turbines successfully demonstrated survivability and energy production, but additional innovations are required to achieve economic viability. The next phase for floating offshore wind technology is now underway with pre-commercial pilot plants, improved turbines adapted for floating applications, and more advanced substructures. The mere fact these multi-turbine, precommercial pilot projects are evolving from single-turbine prototypes is a testament to the viability of FOWT technology. Although the new designs exhibit significant improvements compared with early prototypes, baseline cost analysis does not indicate economic viability without further optimization, innovation, and up-scaling to commercial plant sizes.

The article summarized the current state of floating offshore wind technology and highlights areas for improvement (through innovation or optimization).

- At present, wind turbines on floating sub-structures are identical to fixed-bottom systems, because purpose-built floating wind turbines have not yet been designed or built. The development of a purpose-built floating wind turbine is not expected until there is sufficient market certainty to justify the development risk to original equipment manufacturers (OEMs).
- Offshore hub heights continue to grow because the rotor diameters grow with increasing machine rating, and a sufficient blade tip clearance with the water surface must be maintained. Higher hub heights typically mean wider tower bases, but there are manufacturing and quality-control issues to overcome for large base diameters while keeping modal frequencies away from wave excitation frequencies. For example, rolling and welding thick steel becomes more expensive as sizes and thicknesses increase. To reduce mass and facilitate fabrication, both above and below the waterline, alternative configurations may be sought in the future, including the use of guy wires, lattice towers, prestressed concrete towers (e.g., steel and fiber reinforced), and composite towers. Alternative materials may also help to push natural tower frequencies away from blade passing frequencies and wave frequencies.

- Platform technology is generally based on three classical designs: the spar, semi-submersible, and tension-leg platform (TLP), which are all derived from the oil and gas industry. Many new platform designs seek cost savings by hybridizing of the classical designs to achieve more optimal characteristics. Hybrid concepts may represent a future class of floating wind platforms with transformable configurations adapted to perform under multiple states, including assembly, construction, load-out, and operation on the station.
- For all floating substructure designs, a mooring and anchoring system is used to keep the substructure on the station. A current technology gap is a mooring system design that is effective in shallow water. Mooring technology solutions that can address the transitional depths (50 –100 meters) are critical for floating wind adoption since many existing near-shore lease areas in the North Atlantic Planning Area of the Atlantic Outer Continental Shelf extend into these depths already.
- The adapted fixed-bottom offshore control strategies are most likely suboptimal in floating systems. Control strategies that emphasize co-design, where the entire system and controller are designed together, will offer the greatest performance benefit.
- The goal of the current standards is to ensure survivability. A wide range of designs can meet this minimal threshold, with most of these designs being nowhere close to an optimized solution. Further constraints and guidelines are needed to develop a design that is cost-effective.
- To develop a successful commercial wind project, one needs to not only consider the design of the individual turbine systems, but the design of the entire wind plant. Studies on the wake and array effects to date have focused on land-based or fixed-bottom applications and will need to be revisited for the floating application with compliant motion.
- At the present time, the floating offshore wind industry remains too small to establish its own manufacturing, installation, operation, and maintenance methods.
- Grid integration research is fundamental to understanding the overall value and benefits of offshore wind to the power system.
- As the number of offshore wind installations has grown, so too has the awareness and number of studies about the environmental impact of these installations.

The next generation of floating wind systems is likely to have more flexible substructures, optimized turbine features, and transforming geometries to accommodate a wider range of conditions. Due to the complexity of the problem, a multidisciplinary, multi-fidelity, systems modeling approach with uncertainty quantification is required to reduce the number of viable technologies and identify the most impactful solutions.

4.1.2 Material

The floating substructures (or hull) consist of two types of materials:

- Steel
- Concrete

The design concepts with concrete or hybrid hulls are summarized in Table 17.

Table 17 Design Concepts – Concrete or Hybrid Hulls

Floating Substructure Concept	Material
Hywind	Design 1: steel Design 2: concrete
Toda Hybrid Spar	Hybrid steel and concrete
VolturnUS	Concrete
Ideol Damping Pool	Design 1: steel Design 2: concrete
Saitec SATH (Swinging Around Twin Hull)	Hybrid steel and concrete
Sea Reed	Steel, concrete, or hybrid
Cobra Semi-spar	Concrete
OO-Star	Concrete
SCD nezzy	Concrete
Gicon TLP	Concrete

For the Ideol Damping Pool concept, there are two projects installed, one Ideol Floaten with concrete hull and the Hibiki with a steel hull. A comparison of the Ideol Floatgen and Hibiki is provided in Table 18.

Table 18 Comparison of Ideol Floatgen and Hibiki Projects (Bayard-Lenoir, Chilard, and Swiderski, n.d.; Weller, 2019; Nedo, 2019)

Design Parameters	Floatgen	Hibiki
Year	2018	2019
Power capacity	2 MW	3 MW (2 blades, downwind)
Location	Offshore Le Croisic, France	Offshore Kitakyushu, Japan
Water depth	33 meters (108 feet)	55 meters (180 feet)
Distance to shore	20 kilometers (12.4 miles)	15 kilometers (9.3 miles)
Mass (displacement)	About 6,000 tons	9,858 tons
Draught	7.5 meters	7.5 meters
Hub height	62 meters	72 meters
Substructure length	36 meters	51 meters
Hull material	Concrete	Steel

Design Parameters	Floatgen	Hibiki
Rotor diameter	80 meters	100 meters
Anchor	Drag embedded anchors	Ultra-high holding power anchors
Mooring	6 synthetic fiber (nylon) mooring lines	9 mooring lines catenary (chain)
Inter-array cable	Not applicable	Not applicable
Export cable	Subsea dynamic cable	Subsea dynamic cable

Utsunomiya et al. (2015) summarized the design and installation of the full-scale 2 MW Sakiyama hybrid-spar model. The hybrid-spar consists of steel at the upper part and the precast prestressed concrete (PC) at the lower part. Basically, the design, construction, and installation have been made with great success. However, further cost reduction is necessary for the vast utilization of the same system as part of a commercial power plant in the near future.

Dagher et al. (2017) summarized the design, construction, deployment, testing, retrieval, and inspection of the first grid-connected offshore wind turbine in the US, the VolturnUS 1:8 floating wind turbine. The semi-submersible concrete hull was constructed at the University of Maine Advanced Structures and Composites Center in the winter of 2013. The concrete hull underwent structural qualification testing to confirm structural designs prior to fabrication. After an 18-month operation, the successful decommissioning and recovery of the VolturnUS 1:8 took place on November 4, 2014. Once the VolturnUS 1:8 platform was safely in the dry, the hull was inspected to determine marine growth rates, damage to the concrete hull, including cracking or spalling, steel corrosion rates, and post-tensioning losses.

The concrete hull had not experienced any damage during its deployment, and investigations did not reveal any signs of cracking or spalling. No wear on the concrete was noted, giving confidence that the concrete mix proportions and structural design performed as intended. Corrosion of steel reinforcement was not observed, giving confidence in the corrosion protection methods implemented, including epoxy coatings and grease. Accessible steel reinforcement was measured for corrosion and showed little to no measurable amount of corrosions after 18-months. Lift-off tests for the stressing steel were also completed to determine losses due to concrete shrinkage, creep, steel relaxation, and steel anchorage losses. Steel losses were under the design estimated losses indicating conservatism in the design methodology. Member-to-member connections also appeared to have endured the testing program with no damage or wear again, giving confidence in the materials and design methods implemented. This inspection gives confidence that the material systems, corrosion protection, and design methods provide sufficient robustness.

Dwyer et al. (2017) presented results from an experimental structural testing program to verify the American Bureau of Shipping (ABS) concrete design methodology for FOWTs for the full scale 6MW VolturnUS. Concrete can offer cost-effectiveness, increased durability, and utilize local labor resources to construct prestressed/post-tensioned concrete for the hull structure. Concrete is typically more durable than steel in an offshore environment with little or no maintenance as compared to the traditional 20-year life cycle steel approach. Offshore concrete structures are typically designed to have a 50-70-year service life.

A testing program was developed to verify that the ABS design procedures adequately predict the behavior of the VolturnUS-specific concrete mix and design details when subjected to extreme and fatigue bending loads while maintaining water tightness. The testing focused on bending loads as these are a primary driver for concrete design. Through this effort, the concrete in all cases was found to exceed the ABS prescribed limits for concrete with regard to fatigue, serviceability (including water tightness), and ultimate strength.

For the Ideol designs, the Ideol Floatgen hull is made of concrete, while the Hibbiki hull is made of steel. Choisnet et al. (2016) presented key differences and comparisons for both versions of Ideol's square ring hull designs with concrete and steel. These comparisons are summarized below:

- Concrete as a material for floating structures has the disadvantage that its self-weight for a given volume is larger than for steel structures. The steel hull needs to be ballasted to meet its operational draught. The ballast of the steel hull can be as much as 60-70% of total displacement, while the ballast of the concrete hulls only about 15% of the total displacement.
- Steel plating is fully watertight. Concrete, however, will crack in the most stressed areas. It is consequently necessary to control that these cracks will not cause water leakage into the hull. This is prevented by applying prestressing loads to the structure, which guarantees the water tightness of the hull.
- Corrosion protection is applied to offshore structures to ensure the structure will not corrode during the life of the structure. Epoxy-based coatings and sacrificial anodes protect steel hulls. Steel reinforcements in the concrete hull are protected by adequate concrete coverage of the rebars, ensuring that cracks that may appear on the concrete hull will not open more than pre-set criteria (0.2 to 0.4 millimeters depending on the area and rules), and using cathodic protection for those areas which are exposed to seawater.
- The operation and maintenance of both units will be similar, provided the design life remains within 20 years. For larger lifetimes, the concrete hull will have superior qualities.
- Details of connections for the mooring line foundation and the tower transition piece will be different. Welding is generally used for steel hull, while bolt will be used for concrete hull. The mooring foundations are driven by ultimate loads, whereas fatigue loads define the scantling of the tower transition piece.
- One of the main objectives of wind turbines is to reduce CO_2 emissions in energy production. The carbon content is nearly twice better for a concrete hull.
- The construction methods of the steel hull will be very similar to those of a ship structure. As the hull is made of plated structures fitted with stiffeners, it will be adequately built using shipyard techniques. The main challenge in building concrete hulls is to be able to assemble and launch them. As these hulls are heavy, they cannot easily be handled. There are several

options for the construction of a concrete hull. For mass production, the preferred option is to build the hull in modules that can be more easily transported, assemble them on either a barge or in a dry dock, and float them off.

- The volatility of steel is well known as the steel mills are slow to start or stop. On the contrary, concrete structures are less affected by supply volatility as reinforced concrete structures feature approximately three times less steel, and other constituents are stable in price.
- In general, steel or concrete prove to be equivalent in terms of the performance of a floater.

Proskovics (2018) performed an overview of floating offshore wind technology. As a relatively nascent technology, floating wind has several barriers to overcome before it can be deemed a fully commercial technology. This Analysis Paper looks at the key strengths, weaknesses, opportunities, and threats (SWOT) surrounding FOWTs and their path to full commercialization and is aimed at those who might have technical knowledge of bottom-fixed offshore wind, but little or no previous exposure to floating wind technology. Among these technologies, the advantages and disadvantages of steel and concrete designs were reviewed and compared.

4.1.3 Design Considerations for Fabrication and Installation

Design considerations for fabrication and installation may include:

- Modularized design
- Connection design for components
- No up-ending for concrete spar
- Shallow draft for assembly and tow
- Interface structure design and tolerance for assembly
- Scale (size and weight) restrictions for transport and construction
- Ballast for a different draft for a different installation phase
- Access for inspection

Different design concepts are developed with the goal of easy fabrication and installation. Barge-type design concepts, Ideol damping pool, and Saitec SATH have shallow drafts that can be deployed in shallow water as shallow as 30 meters. Concepts such as TetraSpar, Saitec SATH, SBM TLP, and Gicon TLP apply the modularized design. The TetraSpar design concept is designed with a shallow draft for assembly in port and during tow with a retractable keel deployed at the offshore site. With industrialization design, all components can be fabricated in most factories. For the Toda Hybrid Spar and VolturnUS design concepts, the concrete hulls can be constructed in members and pieces that can be assembled at an inshore site for installation.

Adam et al. (2017) discussed modularity for the Gicon TLP design concept. The main focus of the TLP design is modularity to maximize the flexibility within the supply chain and to have a choice of suppliers for cost efficiency. Furthermore, the fabrication technology should consider common logistical boundary conditions in addition to the limitations and capacity constraints of available fabrication sites.

The design is based on steel-reinforced concrete components. For the modular design of the structure, the principle shape of the design was split into several sections to define the different modules. Pre-stressed, steel-reinforced pipes with bolts at each end are used to design the pipe elements. The new composite pipe will be connected via bolted flanges to the prefabricated steel nodes as a connecting element between the pipes in order to provide the required load support.

4.1.4 Design Analysis Methodologies

This subsection describes the structural design analysis methodologies for FOWTs. Generally, global loads are simulated using integrated analysis (i.e., fully coupled analysis). In an integrated (coupled) analysis, the platform designer normally provides the model of the hull (floating substructure) and the mooring system to turbine manufacturers. Turbine manufacturers then integrate the model with the wind turbine generator model, including the tower and turbine in the analysis. Hydrodynamic pressure loads on the hull are generally calculated by the hydrodynamic program based on potential theory.

Aubault et al. (2009) described the structural engineering that was performed as part of the feasibility study conducted for qualification of the WindFloat technology. Specifically, the preliminary scantling was described, and the strength and fatigue analysis methodologies were explained.

It is assumed that structural loading on the underwater elements of the platform, such as the columns and the water entrapment plates, is mostly dependent on wave loading. Their preliminary design can be conservatively established using design guidelines developed for the offshore industry.

For the truss and the tower of WindFloat, a strength analysis and a fatigue analysis are carried out. A static analysis is sufficient on the truss. However, a dynamic analysis is necessary to account for the excitation of the natural period of the tower. A finite element model of the WindFloat is created. The applied loads are obtained from a time-series of time-domain simulations for each sea-state. External and inertia forces applied to each structural member are computed using dedicated software, based on a time-domain program, which computes hydrodynamic loads by the integration of the diffraction and radiation pressures on each part of the structure.

External forces and moments are applied at the extremities of the tubular elements in the finite-element model or as distributed loads. For the dynamic analysis of the tower, the calculated acceleration load is directly applied at the base of the tower. Additionally, the largest possible wind force is applied horizontally at the top, and the tower supports its own weight as well as the weight of the turbine.

Choisnet et al. (2014) presented the Ideol damping pool design concept, which provides a cost-effective yet robust support to a wind turbine, which features a shallow draft, concrete ring-shaped hull designed for harsh environmental conditions. This paper detailed the features of a 5 MW generic design.

Loads analyses of the generic wind turbine were integrated early in the design process. This enabled to adjust the motion performance of the floater. Specific numerical models were developed and used to derive the global loads transiting through the hull. These models are beam elements with distributed hydrodynamic properties and model the wind turbine in a simplified way. These global loads are combined in partial hull finite element models with local loads such as wave pressure and equipment support loads to detail the structure of the hull. This multiscale approach enables to ensure the global integrity of the structure.

Verifications for the design of the reinforced concrete hull include strength, durability and serviceability to the design criteria. Durability and serviceability verifications include the confirmation that a minimum portion of all the walls' thickness remains in compression to ensure that the hull remains watertight.

It is also verified that the micro-cracks that grow over time in concrete structures remain sufficiently small to prevent excessive water migration through the concrete. The concrete cracks are controlled based on design criteria for strength, fatigue, and serviceability. This guarantees that the concrete and its reinforcements will not corrode during the life of the structure.

A similar procedure would be used for a steel hull, except that the criteria would be the strength of the materials, the prevention of buckling, and the deflection of structures in operational conditions.

Guignier et al. (2016) presented a methodology calculating internal loads, induced by wind and waves, for the Ideol damping pool design concept. The ring-shaped hull is divided into separate compartments on which diffraction radiation is calculated and then used in a time-domain dynamic analysis of the floater, including the wind turbine and mooring system.

A hull is split into 16 compartments based on the physical geometry, allowing internal loads between these compartments to be calculated. The hydrodynamic database is then computed with this multibody approach and finally used in time domain global analysis. The multibody approach is validated by comparing hydrodynamic loads with those obtained with a single rigid body. A time-domain global analysis is performed to obtain the global structural loads. All the load situations are provided as an input for structural analysis of the hull and transition piece. The final structural analysis is made using a detailed finite element model.

Dagher et al. (2017) summarized the structural design analysis of the VolturnUS. The structural analysis procedure is given below:

1. Wind loading from the turbine is applied in a quasi-static manner with an amplification factor to account for dynamic wind effects based on FAST coupled modeling and tank testing data. The turbine, tower, and hull wind loads are included in this way. Turbine loads are calculated using FAST coupled aerodynamic/ hydrodynamic software using multiple long duration time-domain simulations of the fully coupled wind, wave, and current loads. This software has been validated against tank testing data.

2. Wave pressures and accelerations/ inertial loads are calculated using WAMIT wave diffraction analysis software for discrete phase angles of the wave considered.

3. Hydrostatic forces are calculated based on WAMIT predicted dynamic displacements for each phase angle and the mean displacements due to wind and self-weight.
4. All loads from one to three are imported into a quasi-static finite element model, and the member loads are determined.
5. Waves considered include design load cases as well as those recommended for the design wave approach.
6. Slamming loads, tow out loads, and construction loads are considered separately and analyzed using specific models recommended by industry standards.
7. Local connection loads are addressed with sub-assembly finite element models, including global effects.

Hegseth et al. (2018) discussed a simplified method to include distributed, large volume hydrodynamics in the global analysis, where frequency-dependent loads from potential theory are applied on a finite element (FE) model of the hull in a strip-wise manner.

Hydrodynamic forces on large volume floating structures are usually found from potential flow theory and applied in a single point of a rigid body. One drawback of this method is that internal forces in the hull, which may be important for structural design, cannot be calculated in the global analysis. In addition, the flexibility of the floater may affect the dynamic response of the system, especially as turbines increase in size. An alternative is to apply distributed loads from Morison's equation on a beam model. However, though it may give reasonable estimates for the global motions of large volume FOWTs, the approach is only strictly valid for slender structures. To be considered a "slender structure," a structure needs to have a diameter (or the width) of the cross section that is less than 1/5 (0.2) wave lengths. A typical diameter or width of a slender structure is in the range of 2 to 10 meters.

A distributed potential theory is developed, where the loads are found from linear potential theory and distributed over the hull using a sectional approach. This method is compared with a traditional single point load method and Morison's equation method for a braceless 5 MW semi-submersible FOWT. The method is also compared against experimental results from model tests with a focus on internal loads and rigid body motions in the main wave-frequency range. Global motions are accurately estimated by the distributed model for all investigated load cases. Good agreement with experimental results is also seen for the column bending moment in wave-only conditions, although maximum values are significantly underestimated in storm waves due to limitations in linear theory. The results suggest that higher-order wave kinematics are needed in order to capture the extreme bending moments.

The present work is performed for a rigid hull, and structural deformations are thus not considered. However, the distributed potential theory approach may also be used to study the effect of hull flexibility, at least for structures where hydroelasticity effects are not important.

Luan et al. (2018) developed an approach based on an extension of the conventional hybrid frequency-time domain approach, for which the hull is modeled as multibodies. The developed approach can be easily implemented in various state-of-the-art time-domain computer codes for floating wind turbines. This paper intends to provide more information on sectional forces and moments in the hull of semi-submersible wind turbines submitted to combined wind and wave loads by thoroughly analyzing the measurements of the 1:30 scaled model test and corresponding numerical simulations. A Simo/Riflex model that implements the approach has been generated. Sectional forces and moments in five cross-sections of the hull of the braceless semi-submersible wind turbine are analyzed.

Simulated and measured rigid-body motions and fore-aft sectional bending moments of the model in the combined wind and wave conditions are compared. The measured aerodynamic loads are applied to the numerical models. This ensures that the simulated and actual applied aerodynamic loads to the corresponding numerical and experimental models are identical. The differences between the simulated and measured responses are induced by the differences between simulated and actual hydrodynamic loads. Note that the second and higher-order wave excitation loads are not included in the numerical models. In general, the agreement between the simulations and measurements is very good.

The nonlinear wave excitation loads, drag forces, and steady wind and wave loads can induce changes to the mean wetted body surface on the rigid-body motions. These loads can also induce changes to the sectional bending moments. These changes by different load effects are analyzed by comparing measurements in different conditions and by conducting a numerical sensitivity study.

The low-frequency rigid-body motions are dominated by the wind loads, second and higher-order wave excitation loads, and restoring stiffness. In contrast, the resonant motions are sensitive to the damping forces and moments that are empirically modeled by the drag terms of the Morison formula in the developed numerical models. The uncertainties in the simulated and measured low-frequency surge and heave motions have negligible effects on the fore-aft bending moments in the five cross-sections in the hull. The low-frequency fore-aft bending moments are dominated by the wind loads, and pitch motion related fluctuations of gravity forces and hydrostatic pressure forces. The effect of the second and higher-order wave excitation loads on the fore-aft bending moments is observed from the measurements. In general, the effect is relatively limited in the analyzed operational conditions but can be critical in extreme conditions.

The analysis presented in Luan et al. (2018) substantiates that the simulated fore-aft bending moments of the model in the wind and waves could be obtained by superimposing the corresponding simulations of the model subjected to its corresponding wind only condition, and wave only condition except that three constant forces and moments which are the corresponding averaged wind induced forces and moments are applied if the interaction effect between wind and wave loads and/or the interaction effect on the sectional forces and moments are limited. The simplification can significantly reduce the computational cost, but the applicability of the simplification should be analyzed case by case.

Engebretsen et al. (2020) demonstrated the use of Distributed Potential Theory (DPT) in the coupled aero-hydro-servo-elastic time-domain analysis of a spar-type FOWT and illustrated the effect on tower and substructure fatigue life compared to using the classical Morison approach.

The coupled aero-hydro-servo-elastic time-domain analysis is required for a robust design and engineering of FOWTs. For spar-type FOWTs, it is convenient to adopt a nonlinear beam finite element formulation in order to capture the coupled structural response of substructure, tower, blades, and mooring lines accurately.

The DPT approach applies first-order frequency-dependent added mass, radiation damping, and excitation loads distributed over all submerged beam elements in the coupled time-domain simulation, as obtained from diffraction/radiation analysis. This approach, therefore, includes frequency-dependent diffraction effects for all wavelengths, while keeping the substructure flexible, thus enabling hydro-elastic coupling and extraction of internal sectional loads along the substructure.

To cope with the drawbacks of Morison's equation in short waves, fatigue analysis of offshore spar platforms has traditionally been based on rigid body diffraction/radiation analysis. In fatigue analysis of spar-type FOWTs. It is, however, important to correctly capture the first global bending mode of the tower and substructure, as it can be excited by blade/tower interaction. The substructure and tower should thus be modeled by flexible beam elements, rather than as a rigid body.

To calculate sectional loads accurately, a custom script has been developed to integrate the diffraction and radiation potentials over separate sections along the spar, corresponding to each of the beam elements used in the time-domain simulation. In Engebretsen et al. (2020), 33 sections were considered along the length of the submerged body, with finer discretization near the mean free surface. This is called the DPT approach, as it distributes hydrodynamic loads from potential theory along the submerged body in time-domain, instead of lumping the loads to a single point.

To further compare the Morison and DPT approach, a full time-domain fatigue analysis was carried out for the coupled aero-hydro-servo-elastic model in 40 fatigue sea states. The output from each sea state was a time series of 6 degrees of freedom sectional forces and moments along the substructure and tower, as input for structural fatigue analysis. The fatigue assessment focuses on welds and transitions along the substructure and tower.

As expected, the Morison model significantly overestimates the fatigue damage all along the substructure and tower. At the most critical location along the tower, at approximately 1/3 of the tower height, the Morison model overestimates the fatigue damage by 96% compared to the DPT model. At the most critical location along the substructure, the Morison model overestimates the fatigue damage by 73%.

Vasconcelos et al. (2020) presented a structural analysis based on the Finite Element Method (FEM) for the DeepCWind semi-submersible. The DeepCWind structure was developed by the DeepCWind consortium as an initiative to support the research on floating offshore wind technologies. It was used by the Offshore Code Comparison Collaboration Continuation (OC4) as a way to generate test data for validation of offshore wind turbine modeling tools. The results of the experiment allow for a better understanding of offshore floating wind turbine dynamics and modeling techniques, as well as a better awareness of the validity of various approximations. This structure is still under development, and no real scale model has been produced. Nonetheless, a 1:50 scale model was used in 2013 for tank testing. The DeepCWind foundation was designed to support the NREL 5 MW Reference Wind Turbine.

In order to produce the correct inputs to use as loads on the Finite Element Analysis, the FAST code from NREL was used. Three options can be used to calculate the hydrodynamic loads on the structure: potential-flow theory, strip-theory, or a combination of both. The wave kinematics are modeled using the Airy wave theory applied to irregular waves. The loads applied to the structural model include hydrostatic pressure, forces (caused by the mooring lines), buoyancy forces, ballast pressure, and dynamic pressures. Structural analyses were performed for selected load cases, and results were discussed.

4.1.5 Technological Challenges for Structural Design

Currently, technology challenges for structural design are:

- Design optimization for structural design is currently still based on old fashion separated procedures from the oil and gas industry. This may result in conservative designs and increase the cost. To reduce the cost for commercial FOWFs, innovation and optimization based on a multidisciplinary, multi-fidelity, systems modeling approach with uncertainty quantification are needed.
- Considerations of the manufacturing process and subsequent transportation and installation should be included in the design process.
- Consideration of flexibility of the hull is not fully incorporated in the integrated analysis tools. Integrated design tools up to the structural design level are not available and not streamlined.

4.2 MOORING AND ANCHORAGE DESIGNS

The following section provides an assessment of the technological issues for FOWT mooring and anchorage designs:

- Configuration of mooring system (spread mooring, single point mooring, etc.)
- Shallow water mooring system design
- Material (synthetic rope, chain, clump weight)
- Anchoring system (shared anchor)
- Design considerations for installation

4.2.1 Mooring Systems

From the review of different design concepts, there are several mooring system configurations:

- Spread mooring system

- Single point mooring system
- Turret mooring system
- Tension leg system

These mooring systems are similar to systems used in the oil and gas industry. There are also differences with regards to material and applications:

- Conventional materials, such as chain and wire rope, are applied in tension leg system for tension leg platform (TLP)-type FOWTs. This type of application is new for TLP.
- New materials such as polyamide (Nylon) ropes are used in the design, especially for shallow water mooring systems.
- New configurations with a combination of chain, wire rope, fiber ropes, clump weight, and buoys are used to design the mooring system in shallow water.

Homb (2013) investigated the fatigue damage based on Nonlinear Time Domain, and Frequency Domain approaches for the Hywind Demo project. The results from this fatigue calculation showed similar results as Statoil's own results (compared with a fatigue evaluation based on the Rainflow technique). A parameter study of the clump weights revealed that it is not optimized in terms of fatigue.

Calculating the fatigue damage in the frequency domain was based on a closed-form solution. The solution was to filter the "slow-motion" and the "wave-motion" processes apart, then calculating the contributions from the two processes individually. The results from this method gave only slightly lower results than the results from the rainflow-technique on the nonlinear time-domain analyses.

Maine Marine Composites, LLC. (2015) described four case studies in which software tools were used to simulate prototype FOWTs in an attempt to predict motions, fatigue damage, and extreme strains to the mooring components on such a system. Two key factors that can affect the fatigue life of FOWT mooring systems have been identified and focused on in this project: snap (shock) loads and chain abrasion. Failure modes in shallow-water mooring systems include the fatigue of chain links near the touchdown point, long-term damage due to cyclic and shock-induced tension variation, and damage due to the abrasion of the laid length dragging transversely on the seafloor.

A parametric fatigue lifetime calculation was conducted based on available field measurements for environmental parameters. Several significant conclusions are drawn from the fatigue study, including severe storms, which contribute a disproportionate amount of damage, even when accounting for their low likelihood of occurrence. In one case, assuming 50% of the expected corrosion when calculating fatigue lifetime substantially over-estimated the lifetime compared with a similar calculation in which the corrosion damage at each year was accounted for. An assumption of 65-70% would have been more accurate in this case.

The project team found that commercial software tools are reasonably accurate, provided that the inputs (environmental, mooring, platform, turbine) are known and accurate. System-level abrasion and corrosion are not addressed in the common software tools. The project team found that good knowledge of the local environment is essential even for preliminary design, much less detailed design. Simulation results were extremely sensitive to sea-states and to the relative headings between storm directions and the mooring system. The project team found that the mooring line tension history with snap events has a higher exceedance probability at the high tension range than the mooring line tension history without snap events. That means snap loads should be considered as part of the effect on fatigue life.

Hsu et al. (2017) investigated mooring line tensions measured during experiments conducted on a 1:50 scale semi-submersible FOWT under survival storm conditions (i.e., a 100-year storm). Several snap events are found to result in the windward mooring line. The duration of these events ranges from 7.5 to 10.5 s, and the maximum tension values recorded are 37-68% higher than the corresponding cyclic non-snap tension maxima. A composite Weibull probability distribution is proposed for the mooring line dynamic tension that incorporates the effects of snap events.

A snap event is characterized by a spike in tension that occurs over a very short duration, as a mooring line re-engages immediately following a slack condition. Such an impact can result in a shock on the line material leading to immediate/catastrophic failure or a considerably reduced service life. The investigation of the extreme value distributions of mooring line tensions indicates that including snap-induced tension maxima in strength analysis of the mooring system may prove to be significant.

Skaare (2017) pointed out that one challenge in Hywind concept development that was experienced in early numerical simulations with larger turbines placed on top of a more optimized foundation and mooring system than the Hywind Demo was large yaw motions. These were related to the slowly varying spatially distributed wind field over the larger rotor area – an effect that is expected to become even larger within a wind farm with wake effects from adjacent wind turbines. One could rather easily avoid the large yaw motions by increasing the yaw stiffness in the mooring line by increasing the pretension in the lines, but this could lead to a negative and expensive design spiral for the mooring system.

These challenges triggered the development of a patented multi-degree of freedom motion control system for Hywind that takes advantage of individual blade pitch control for yaw motion control. The use of individual blade pitch control will lead to increased use of the blade pitch system with corresponding increased fatigue damage of the blade bearings. Therefore, a careful selection of the mooring line pretension and the activation limit for the yaw motion control system must be made for the wind turbine model, and the site considered to avoid exceedance of the capacities of the blade pitch actuators and blade bearings.

The selected mooring system for Hywind Scotland has a conservative design that is not dependent on the application of yaw motion control, but when the technology is successfully tested in full scale, it can be used as a basis for a more optimal mooring design in future projects.

Choisnet et al. (2018) described how the seakeeping performance of the floater and the mooring system material are validated step by step to mitigate risks and increase the learning effect of the Floatgen project in shallow waters in a severe environment. The floating wind turbine includes a

2MW Vestas V80 turbine installed on top of a concrete hull, moored by means of polyamide mooring lines.

The mooring system comprises three groups of two mooring lines. The mooring lines are made out, from anchor to the platform, of drag embedment anchors, studless chain, a length of polyamide rope, and a top chain segment. There are also buoyancy elements distributed along the lines that prevent chafing damage of the ropes on the seabed, and counterweights in the lines to keep the line under tension. In the frame of the project, the mooring system was designed by Ideol, and Ecole Centrale de Nantes (ECN) procured the mooring lines and their offshore installation.

Pre-existing research had already quantified the good fatigue performance of nylon ropes. The validation steps included laboratory tests to assess the stiffness and stretching force needed to avoid re-tensioning the lines during the life of the floating wind turbine. Tests are also enabled to accurately quantify the stiffness of the lines and their evolution over time in the specific loading context of the project.

During offshore installation, the lines were stretched up to the maximum storm-force, which enables to embed the anchors and, at the same time, stretch the ropes so that their length remains constant over the life of the floating wind turbine. In addition to the stiffness of ropes at high loads, the applicability of the rope creep measured in the laboratory, and the stiffness at low loads can also be ascertained during the mooring lines installation. During the mooring lines connection phase, load/extension tests were performed under tension around the hook-up tension. This enables the confirmation of the stiffness of the rope and the length at low load. After these tests, the ropes could safely be cut at the required length and connected to the wind turbine. The tests revealed that the stiffness at low load was within 5% of the expectations, as derived from laboratory tests. The length of the lines is within 0.2% of predictions, which corresponds to the position measurement accuracy of the anchor. It was then decided to use the theoretical values.

A series of tests were done in the harbor and on-site during commissioning in order to validate the behavior of the turbine in its floating configuration. Turbine components include a number of sensors that enable the comparison of measurements to coupled calculations. The elementary verifications made in the laboratory during installation and construction enabled the validation of the behavior of the mooring lines, floater behavior, and floating wind turbine dynamics. This consequently limits the risks during power production at sea, to the combination of wind and wave events.

Weller (2019) reviewed fiber rope selection for offshore renewable energy. There are current research and development efforts to advance the qualification of Nylon rope in the design of Nylon based mooring systems. The Technology Qualification (TQ) includes risk assessment, TQ plan development, qualification activities for rope testing of rope properties, abrasion, stiffness, fatigue performance, creep, etc. These technologies were applied to the Ideol Floatgen project using Nylon ropes in the mooring system. Future needs for the qualification of new fiber rope technologies, especially Nylon ropes, are proposed.

Bach-Gansmo et al. (2020) used three different mooring set-ups to experimentally investigate the influence of two parameters, namely the mooring line angle and line pretension, for a taut mooring configuration focusing on the dynamic response when applied to the TetraSpar floating foundation compared to a catenary mooring system. The study uses physical experiments and numerical codes to investigate the mooring and floater response when moored with elastic mooring lines.

During the experiment, some uncertainties were present, but the overall behavior proved great potential for the taut compliant mooring lines in terms of the hydrodynamics and maximum line loads. The footprint could be highly reduced and showed a reduction of 2/3 compared with the original catenary station keeping system. The drawback of the investigated configuration was the higher pitch amplitudes in the response amplitude operator, which can be linked to higher accelerations in the tower. However, the angle and pretension had a relatively modest influence on the natural periods, apart from the yaw degree of freedom. With all the above mentioned, the motivation for developing even more compliant materials is evident, as the ease of final design with a low footprint will be more achievable. A taut configuration with highly compliant mooring lines has, therefore, proved to have a large potential as an alternative to the catenary mooring, and further research is encouraged.

West et al. (2020) investigated the synthetic mooring line stiffness models recommended by the design guides and their influence on FOWT global response. Synthetic fiber ropes are extremely nonlinear materials with responses that are complicated to predict. When synthetic mooring line technology was being explored by the offshore oil and gas industry, the fibers that were of interest were mainly polyester, Dyneema, and aramid fibers. For FOWTs in shallow to modest water depths (45 meters – 80 meters), these materials tend to be far too stiff, and other options will need to be explored.

For the study, fully coupled simulations using the University of Maine's VolturnUS concept with various mooring line stiffness models were run. For these simulations, two design load cases (DLCs) were chosen. First, it includes an operational case at the turbine's rated wind speed, which strongly influences fatigue loading. Second, it includes an extreme operation case. The rope data utilized corresponded to a 155-millimeter nylon line of parallel strand construction.

There are a few key findings from these results. First for larger sea states, the model chosen is more important for predicting accurate responses. For each of these two load cases, results for the smaller sea state are actually quite close. The stiffer upper bound stiffness model for the larger sea states leads to greater nacelle accelerations and surge responses. This makes intuitive sense as one would expect stiffer lines to attract more loads to the systems and lead to greater accelerations. The stiffer mooring systems will to lead to larger forces on the platform, and thus, larger accelerations.

The next interesting finding involves the low-frequency response for surge being shifted depending on the stiffness model used. Stiffer models lead to a higher natural frequency than more compliant stiffness models. Surge natural frequency depends on the mooring system, which depends greatly on the stiffness of the line. When checking resonance issues on the FOWT, this could be problematic as the current recommended stiffness values do not agree. The simulation results presented suggest that in order to be able to accurately predict the FOWT response, the rope stiffness models in large sea states that control the design stiffness models must be updated for fully coupled simulation software.

Corewind (2020) reviewed the current mooring and anchoring state of the art for floating wind projects currently installed or in the construction phase. The industry design standards are also reviewed. The report summarized installation and inspection techniques for semi-submersible and spar floaters. Technical challenges are also discussed.

Tajalli et al. (2020) performed a study on potential earthquakes, landslides, tsunamis, and geohazards for the U.S. offshore pacific wind farms. This report provides guidance by identifying the best current practices regarding the geologic hazards posing risks to components of FOWFs, including floating structures, mooring system, anchoring system, and cables.

4.2.2 Anchorage Designs

The anchorage systems for different design concepts include:

- Drag embedment anchor
- Suction anchor
- Anchor pile
- Shared anchors

Fontana et al. (2016) introduced a mooring and anchoring concept for FOWTs in which each anchor moors multiple floating platforms. A preliminary analysis of the potential economies of such a system and the impact of such a system on anchor loads is presented. The key concept of the system is that FOWTs could share anchors, resulting in each anchor in a FOWF serving multiple platforms and generating economies in the number of site investigations required and the number of anchors required.

The example platform used here is a semi-submersible based on the OC4/DeepCWind design that supports the NREL 5 MW tower and turbine. The platform is moored in 200 meters of water by three lines spaced evenly. Platform dynamics for the turbine in an operating state are simulated using FAST for two wave/wind direction. Wind and wave fields are assumed to be co-directional. A simple approximation is developed to give initial insights into the loads that arrive at an anchor in a multiline wind farm. It is assumed that each FOWT is subject to independent wind and wave fields. The net forces on each anchor are calculated based on the time history loads of each line connected to the anchor.

The multiline anchors will, as expected, have to resist significant loads from multiple directions, but that the characteristics of those loads (mean and coefficient of variation) may not be consistent across all directions. Preliminary analysis indications are that multiline anchors may be able to be designed for reduced overall capacity but must be able to retain that capacity through a range of loading directions.

Utsunomiya et al. (2017) presented an outline of the demonstration test for using a suction anchor and polyester rope in a floating wind mast (that was converted from a floating wind turbine). The location of the demonstration site is about 1 kilometer off the coastline of Kabashima, Goto City, Nagasaki prefecture, Japan. The site has been used for the demonstration test of floating wind turbines. The floating wind mast was converted from the half-scale FOWT. For this demonstration test, one of three mooring lines was replaced by a combination line of anchor chain – polyester rope – anchor chain system with an intermediate clump weight and a suction anchor at the end.

The basic design methodology for the mooring line, including polyester rope and suction anchor, has been presented. A specimen test for polyester rope has been made. Considering the marine soil investigation result, the profile of the suction anchor was determined to be somewhat short and wide dimensions. Installation of the suction anchor was successfully made at both the test site and the targeted demonstration site. The installation of polyester rope was also made successfully.

Shimada et al. (2018) presented a preliminary design of a shared pile anchor made based on the result of dynamic mooring simulation. It was found that a simple empirical design formula of an optimum pile specification can be established, which is useful for preliminary estimation of the installation cost.

The wind turbine and a floater that were analyzed are 2 MW semi-submersible "Mirai." Although six chains are used for mooring in "MIRAI," for sharing of an anchor, in the study, three-direction mooring, which unites two chains, is used. Based on the maximum tension acting on anchors, a preliminary design of a pile is made. An empirical design formula relating to the optimum pile dimensions useful for estimating the installation cost was developed.

Arany and Bhattacharya (2018) provided a methodology with which the designer of the anchors can easily and quickly assess the expected loads on the foundations. Analysis of loads and motions of FOWTs is a challenging task, and typically requires a coupled aero-servo-hydro-dynamic analysis. Furthermore, anchor design requires incorporating soil-structure interaction (SSI) in the analysis. It is important to have a simplified methodology for estimating the loads on the anchors in order to generate conceptual anchor designs for feasibility studies and the early phases of design. This paper aims to provide a simplified approach for finding an upper bound limit for the expected loads on the FOWT structure.

For this purpose, a combination of a quasi-static wind load analysis and Morison's equation for wave load estimation using Airy waves is employed. Dynamic amplification is also considered, and design load cases are established for ultimate limit state (ULS) design. A simple procedure is also presented for sizing suction caisson anchors. All steps are demonstrated through an example problem, and the Hywind case study is considered for such purpose.

Balakrishnan et al. (2020) studied the applicability of the novel multiline anchors concept to spar substructures. Time history of anchor forces for various simulations are compared with those found in the study on multiline anchor with semi-submersibles. The model chosen is the OC3 Hywind with the 5-MW NREL offshore turbine in 200 meters water depth. The platform is supported by three catenary mooring lines, which are placed at 120° apart. The multiline anchor is studied for its effectiveness in terms of anchor tension forces and direction of anchor force. Multiline anchor force dynamics are simulated with NREL's FAST.

Damiani et al. (2020) presented a project on a concrete 3D print suction anchor (3DSA). The project aims to prove feasibility, manufacturability, and cost savings for a 3DSA that:

1. Reduces anchor manufacturing and installation costs by up to 80%
2. Works with all floating wind turbine designs and water depths
3. Facilitates mass production in Scottish harbors with domestic materials

4.2.3 Design Considerations for Installation

For a FOWT, one of the considerations of the mooring system design is safe and robust installation and disconnection.

For the Hywind Scotland project (MacGregor, 2016), the mooring system was designed to take considerations for the installation:

- Without large winches on wind turbine
- Without diver intervention

For each FOWT, two adjustable fairlead chain stoppers were used on one of the three mooring lines (see Figure 32).

After the connection of the first mooring line and the second mooring line, the third mooring line will be connected to a forerunner through a Fairlead Chain Stopper towards the vessel winch wire. The vessel will heave the winch wire until the chain is connected and tensioned to the design pretension value. This mooring tensioning process is shown in Figure 33 (Statoil, 2015).

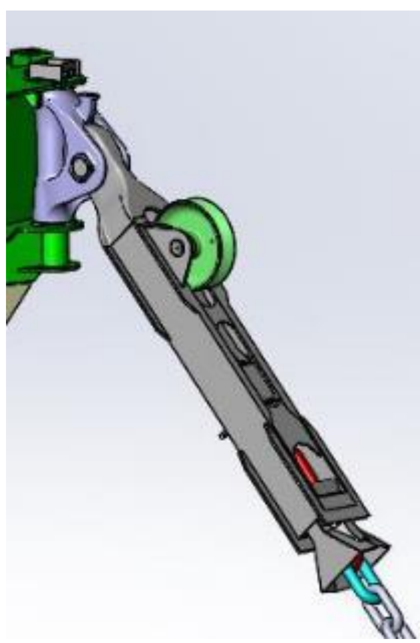


Figure 32 Adjustable Fairlead Chain Stopper – Hywind Scotland Project (MacGregor, 2016)

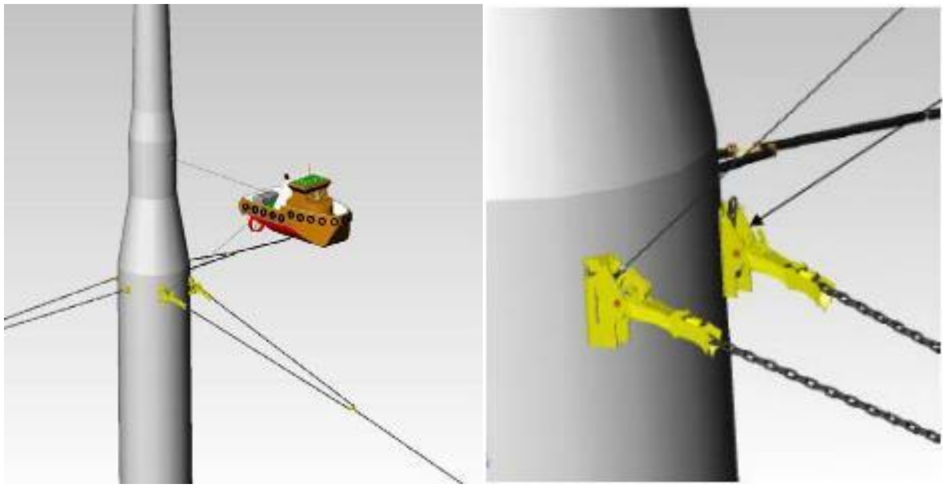


Figure 33 Mooring Tensioning Process – Hywind Scotland Project (Statoil, 2015)

For the WindFloat Atlantic project, First Subsea is supplying Platform Mooring Connectors (PMCs) (EDP, 2020). The Platform Mooring Connector allows the mooring lines to be pre-laid on the seabed, prior to the arrival of the FOWT. With the platforms in position, the end of the mooring line can be picked up from the seabed and pulled into the PMC located on the platform's hull structure. Once in place, the connector is automatically engaged and ready for service.

For the Hywind Tempen project (Equinor, 2019), the mooring design is improved from the Hywind Scotland project (see Figure 34)

- Bridle wire
- In-line tensioner
- Shared suction anchors

Figure 34 Hywind Tempen Mooring (Equinor, 2019)

4.2.4 Technological Challenges

The technical challenges for mooring and anchoring systems are:

- The design of shallow water mooring systems can be challenging. New configurations and new material can be further studied for shallow water mooring.
- The possible different failure modes with different load characteristics may be further studied and should be addressed in the design phase of the projects.
- There is a lack of experience in using new material for long-term moorings. Testing procedures and data for design are to be developed and accumulated to support the long-term use of the new material.
- There is a lack of experience in shared anchor design. Design procedures and criteria should be developed.
- The certification and testing procedures of new designs, components, and connectors need to be developed.

4.3 DYNAMIC POWER CABLE SYSTEMS

The following provides an assessment of the technological issues for the dynamic power cable system:

- Current technology and limitations (for example, rated voltage)
- Power cable system configuration
- Dynamic analysis consideration

The projects and research findings are reviewed to assess the current state-of-the-art technology and limitations of the current technology. A literature review is performed to address the dynamic analysis consideration.

4.3.1 Electrical Infrastructure for Commercial FOWF

There are currently no utility-scale commercial FOWFs in the world. Similar to (fixed) offshore wind farms, the following electrical infrastructures are needed for a utility-scale commercial FOWF (BOEM, 2018; Renews, 2016):

- Wind turbine generators (WTGs)
- Inter-array cables (array cable)
- Offshore substation (floating, fixed or seabed mounted depending on water depth variation toward shore, if needed)
- Export cable (connection to onshore substation)
- Onshore substation
- Connection to the grid

An informational depiction of electrical infrastructure for a FOWF is shown in Figure 35.

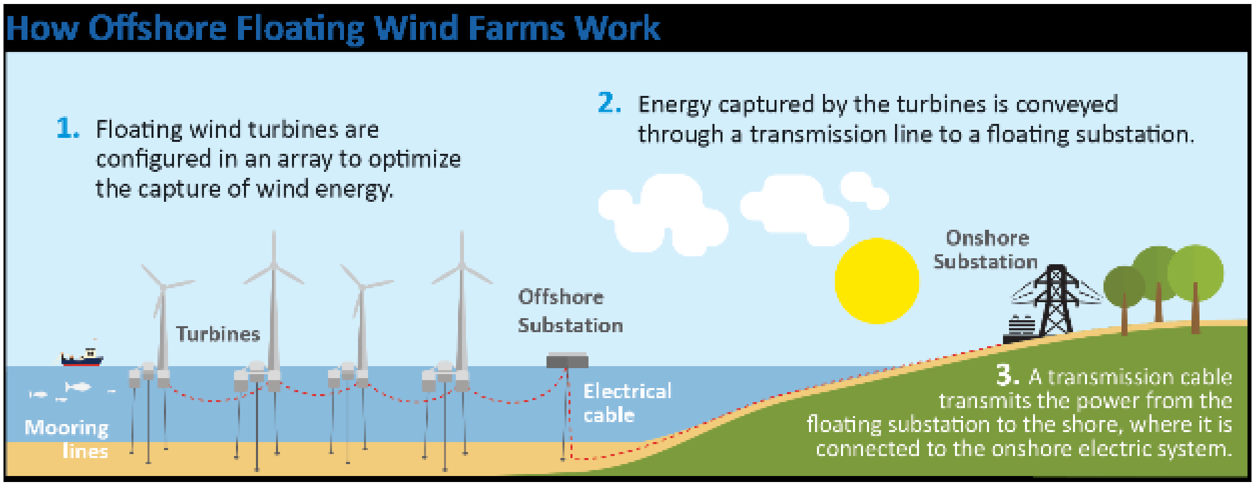


Figure 35 Informational Graphic on How FOWFs Work - – BOEM (2018)

The wind turbine electrical system is the electrical equipment internal to the wind turbine, up to, and including the wind turbine terminals, including equipment for earthing, bonding, and communications.

The Wind turbine generator (WTG) converts kinetic energy from the wind into three-phase AC (Alternating Current) electrical energy. The power take-off (PTO) system receives electrical energy from the generator and adjusts voltage and frequency for onward transfer to the wind farm distribution system. Where the turbine voltage rating does not match that of the wind farm array, transformers are often placed in the nacelle, or sometimes at the base of the tower. Typically, they transform from a low voltage (0.69kV to 3.3kV) to 33kV or 66kV for distribution around the wind farm array.

All wind turbines have a control panel at the tower base to facilitate on-site control of the turbine by maintenance staff without climbing the turbine. For many turbines, the space near the base of the tower is used to mount various elements of the power take-off, including convertor and cooling systems.

For offshore wind, high voltage (HV) typically refers to any cable rated higher than 66kV, and low voltage (LV) refers to anything below 11kV. High voltage (HV) cables are generally associated with transmission networks and export cables. Medium voltage (MV) is associated with distribution networks and array cables. The wind turbines generate at low voltage (LV) with a transformer at the base of the tower stepping up voltage to medium voltage (MV).

The export cable connects the offshore and onshore substations. The subsea export cable may connect to the land cable through a transition joint at the shore landing point. The offshore substation transformer steps up the voltage from the array cable when needed. High Voltage Alternating Current (HVAC) export cables are typically rated between 132 kV and 245 kV. HVAC cables suffer important power losses over longer distances. For fixed offshore wind farms, export cables with High Voltage Direct Current (HVDC) technology are used for long-distance transmission. For example, the UK's 3.6 GW Dogger Bank offshore wind farm located some 130 kilometers off the northeast coast of England will be equipped with HVDC technology for power transmission from the wind farm to the onshore grid without significant power losses.

The boundary of the power cable system starts at the wind turbine terminals and ends at the network connection point at the onshore substation or the shore landing point where the subsea export cable connects to the land cable through a transition joint. The array cables start at wind turbine terminals and end at the connection point at the offshore substation (if needed) or a subsea hub, or a subsea joint to the export cable. The export cable starts at the connection point at the offshore substation and ends at the connection point at the onshore substation or at the transition joint to the land cable.

Cable protection systems (CPS) such as bend stiffener and bend restrictor provide protection to cables at vulnerable locations, from the wave and tidal action, and when the cable enters the wind turbine or offshore substation aperture or J-tubes.

For example, the power cable system of the New England Aqua Ventus I wind project is shown in Figure 36 (DOE, 2017). The proposed wind farm has two wind turbines, each with a rate power of 6 MW. Each turbine has an export cable for transmitting power at 34.5 kV, 3-phase Alternating Current (AC), and is roughly four inches in diameter and armored. The cables are supported in the water column with a series of clamp-on buoyancy modules or floats along the length of the cable to a seabed hub installed on the sea floor. The seabed hub connects the 6 MW export cable from each turbine and the associated fiber optics to a 12 MW subsea export cable, approximately 5.5 inches in diameter.

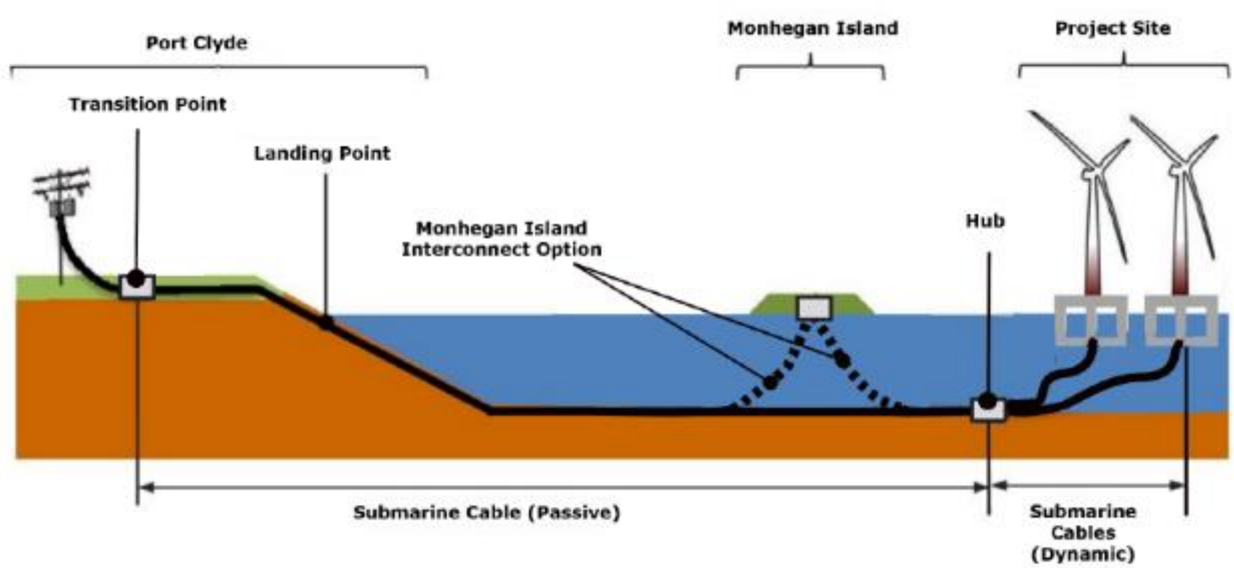


Figure 36 Components of Project Electrical Interconnection – New England Aqua Ventus I Wind Project (Durakovic, 2020)

HVDC is used for long distance transmission because the full capacity of the cable system can be used for transferring active power. HVDC converter offshore substation may be installed to convert AC into DC before connection to the export cable. HVDC converter stations are expensive. The use of an HVDC converter station depends on the offshore wind farm size and distance to the shore. HVDC BorWin1 is the first HVDC facility in the world installed in 2009 with a power capacity of 400 MW at a bipolar voltage of ±150 kV for importing power from an offshore wind farm to shore (Wikipedia, n.d.). Although HVDC technology is considered mature for fixed offshore wind farms, the technology is not available for dynamic applications for FOWFs. Current dynamic subsea power cables are all based on AC technology.

4.3.2 Current State-of-the-Art Technology

4.3.2.1 Case Studies

There are a limited number of installed FOWT projects. Among these projects, most of the projects are small scale or demonstration projects with only one turbine, which was connected through a medium or low voltage (33 kV or lower) export cable directly to the shore and gird.

Among these projects, the Fukushima FORWARD, the Hywind Scotland, and the WindFloat Atlantic projects use both inter-array cables and export cables up to 66 kV rated voltage. These projects represent the current state-of-the-art technology for FOWFs and thus are reviewed in detail in this section. The voltage of array and export cables of these three FOWFs are summarized in Table 19. The Kincardine project, which is still under construction, is using the same power cable technology as Hywind Scotland and WindFloat Atlantic. The same also applies to the four French pilot floating offshore wind farms that are under development for near-future deployments.

Table 19 Power Cables for FOWFs - Installed

Project	Year	Distance To Shore	Water Depth	Turbine Power	Array Cable	Export Cable	Floating Substation	References
Fukushima FORWARD	2013	23 kilometers (14.3 miles)	110-125 meters (361-410 feet)	14 MW	Furukawa Electric, 22 kV AC	Furukawa Electric, 66 kV AC	66 kV, 25MVA	(Furukawa Electric, 2019; Fujii, and Tanaka, 2013; Ocean Energy Resources, n.d.)
Hywind Scotland	2017	25 kilometers (15.5 miles)	95-120 meters (312-394 feet)	5×6 MW	Nexans, 33 kV AC	Nexans, 33 kV AC	Not applicable	(Statoil, 2015; Nexans, n.d.; Power-technology, n.d.)
WindFloat Atlantic	2019	20 kilometers (12.4 miles)	85-100 meters (279-328 feet)	3×8.4 MW	JDR, 66 kV AC	Hengtong, 150 kV AC	Not applicable	(JDR, n.d.) (Offshorewind, 2018; Offshore Wind Industry, 2017)

Fukushima FORWARD project has the world's first and only floating substation with a rated voltage of 66 kV and rated power of 25 MVA. The Fukushima FORWARD project consists of three FOWTs with rated power at 2 MW, 5 MW, and 7 MW, respectively (Fukushima Offshore Wind Consortium, n.d.). The power cable system arrangement of the Fukushima FORWARD project is shown in Figure 37. The 66kV transition joint between dynamic and the static submarine cable is shown in Figure 38.

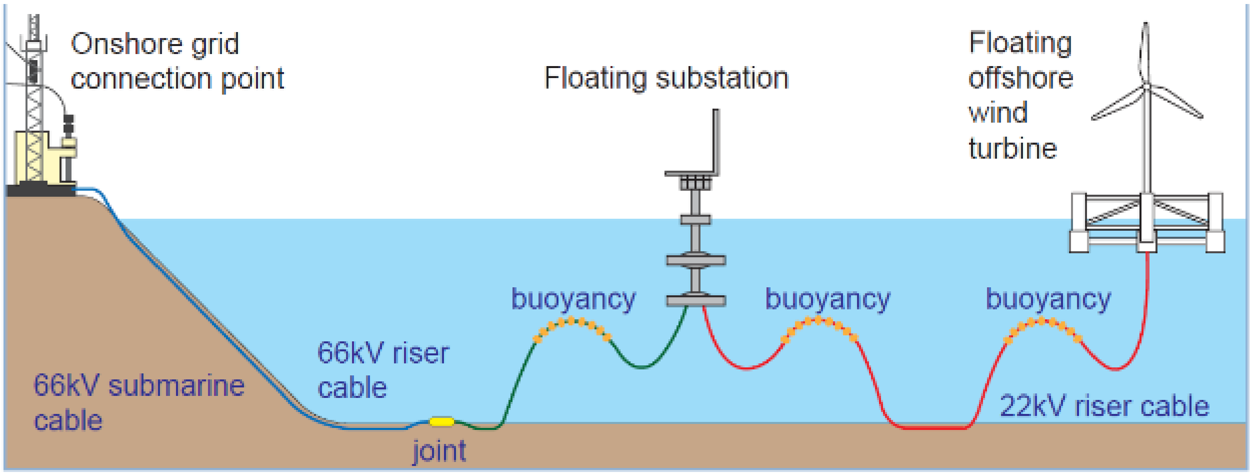


Figure 37 Fukushima FORWARD Project Power Cable System (Fukushima Offshore Wind Consortium, n.d.)

Figure 38 Fukushima FORWARD Project 66 kV Transition Joint (Fujii and Tanaka, 2013)

First Subsea cable bend stiffener connectors (Offshore Energy, 2015) were used to connect 22 kV cable to the wind turbines and the floating substation, and a cable bend stiffener connector for a 66 kV cable connection to the floating substation. The First Subsea cable connector has a self-activating ball, and taper mechanism allowing deployment offshore without the use of divers or underwater remote operated vehicles. The male connectors are guided into receptacles on the wind turbine and substation and, once engaged, cannot be released until the load has been removed. A simple disengage mechanism allows the connector to be disconnected and recovered for re-use. The 66 kV cable connector (bend stiffener) is shown in Figure 39.

Figure 39 Fukushima FORWARD Project 66 kV Bend Stiffener Connector by First Subsea (Fujii and Tanaka, 2013)

Hywind Scotland Pilot Park consists of five 6 MW wind turbines, which are located off the east coast of Scotland, approximately 30 kilometers from Peterhead in Aberdeenshire. The export cable comes ashore at Peterhead and connects to the local distribution network at Peterhead Grange substation. The onshore project infrastructure comprises an underground cable approximately 1.5 kilometers in length and a small switchgear yard facility close to the Peterhead Grange substation. A schematic illustrating the overall project is provided in Figure 40 (Statoil, 2015).

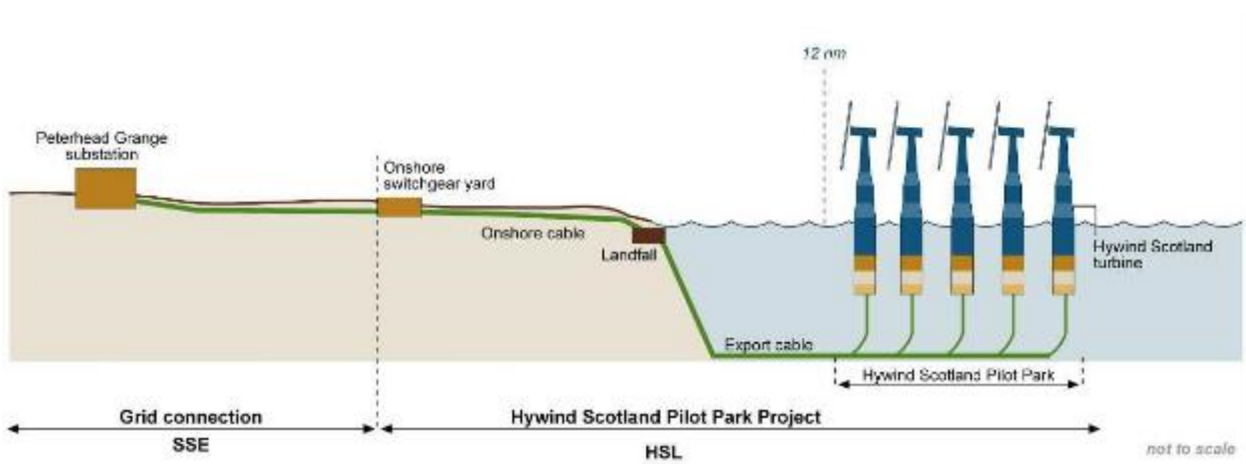


Figure 40 Key components of the Hywind Scotland Pilot Park Project (Statoil, 2015)

The WTGs are connected by array cables. The array cables are arranged in a ring circuit configuration. The array cables utilize buoyancy elements to maintain location and configuration. Figure 41 (Statoil, 2015) illustrates the dynamic section of the subsea cable and how it is suspended in water. This figure shows how the cable is laid in a "lazy-wave (s-shape). The purpose of the "s-shape" is to allow the floating structure to move without stretching or snapping the cable. The cable touchdowns on the seabed approximately 250 meters from the substructure. From the seabed, close to the bottom touchdown, a small anchor is used to stabilize the cable. Then there is a section of the cable where buoyancy elements are installed. These buoyancy elements lift the cable from the seabed and suspend it in the water well below the sea surface. There is a cable section without buoyancy elements where the cable drops towards the seabed before the cable rises and is pulled into an I or J-tube on the outside of the substructure. The export cable is terminated on one of the WTGs. The export cable transports electricity from the Pilot Park to a landfall located along the coast at Peterhead.

Nexans (n.d.) supplied the static and dynamic cabling and associated accessories for the world's first FOWF.

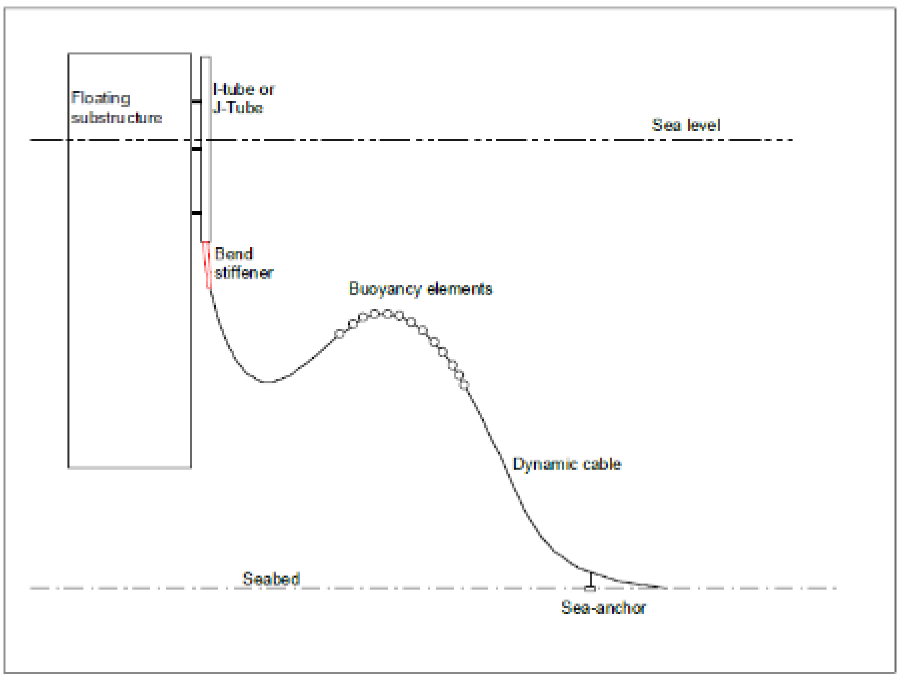


Figure 41 Schematic of the Attachment of the Array Cable to the WTG (Statoi, 2015)

WindFloat Atlantic (WFA) consists of three 8.4 MW turbines, the world's largest installed on a floating platform, is located 20 kilometers off the coast of Viana do Castelo in Portugal. The WFA wind farm with the first platform successfully connected on December 31, 2019, and the third in July 2020 is able to supply to the grid in Portugal (Offshorewind, 2020c).

China's Hengtong has been awarded a contract by REN – Rede Electrica Nacional, S.A., the operator of transmission grids in Portugal, to design, manufacture and install the submarine export power cable system for the WFA floating wind project. Hengtong was constructed and installed at 18 kilometers, 150 kV submarine cable connection offshore Viana do Castelo, which links the 25 MW floating wind farm to the onshore grid (Offshorewind, 2018a).

The cable supplier JDR Cables supplied the innovative 66 kV technology to dynamic cabling for the WFA wind farm (JDR, n.d.; Offshore Wind Industry, 2017). This marked the world's first application of dynamic cables operating at 66 kV. The scope of supply includes the design and manufacture of array cables to suit the three WindFloat semi-submersible platforms, supporting V164 8.4MW wind turbines. The floating wind turbines will be connected via a network of array cables to one export cable.

To support the project, JDR has designed a unique, easy to install, dynamic cable breakaway system, which protects the floating platform in the unlikely event of a mooring line failure. Under extreme load conditions, the breakaway system disengages the cable hardware at the top and bottom of the I-tube and allows the cable to drop to the seafloor, preventing it from exerting excessive tensions on the floating structure in case the platform floats off position. JDR's proposal also includes HV termination and testing.

Trelleborg delivered dynamic cable protection products, including Distributed Buoyancy Modules (DBM), bend stiffeners, and Uraduct for the WFA project (Trelleborg, 2019).

WFA brings together two pioneering developments in array cables: dynamic cable design for FOWTs and high-voltage power transmission, through 66 kV cable technology.

Two more WindFloat floating wind farms, the 50 MW Kincardine Project in Scotland and 30 MW Golfe du Lion (EFGL) Project in the south of France, will come online between 2020 and 2022.

4.3.2.2 Inter-Array Cables

The array cable creates loops or individual strings connecting all wind turbines to the offshore substation. The array cables are medium voltage (MV) AC cables. Array cables are now typically rated at 66 kV. The first generation of offshore wind farms typically used 33 kV.

According to Ferguson et al. (2012), the benefits of moving the inter-array voltage from 33 kV to 66 kV AC for large offshore wind farms are:

- Cost reductions
- The potential for higher voltages (48 kV or 66 kV) to be used to connect wind farms without an offshore substation
- Reduce the number of cable strings entering a substation as more wind turbines can be connected per string
- Reduce system loses
- Increase availability
- Reduce overall cable length
- Reduce the number of substations

The first application of 66 kV inter-array for a fixed offshore wind farm is the Blyth offshore wind farm in 2017 (Nexans, n.d.(a))

The first application of 66 kV inter-array cable for a FOWF is the Fukushima FORWARD project in 2013.

4.3.2.3 Export Cables

HVAC export cables are typically rated between 132 kV and 245 kV (ABS, 2012; Skaare, 2017). The voltage for subsea HVAC cable is up to 420 kV (Nexans, n.d.(b)). HVAC cables suffer important power losses over longer distances. Ackermann et al. (2005) compared the different technical solutions for a 500 MW and a 1000 MW wind farm with different distances to shore (up to 200 kilometers). The HVAC solution results in lower losses for distances up to approximately 70 kilometers (Ackermann et al., 2005; Wave Energy Scotland, 2018), as shown in Figure 42.

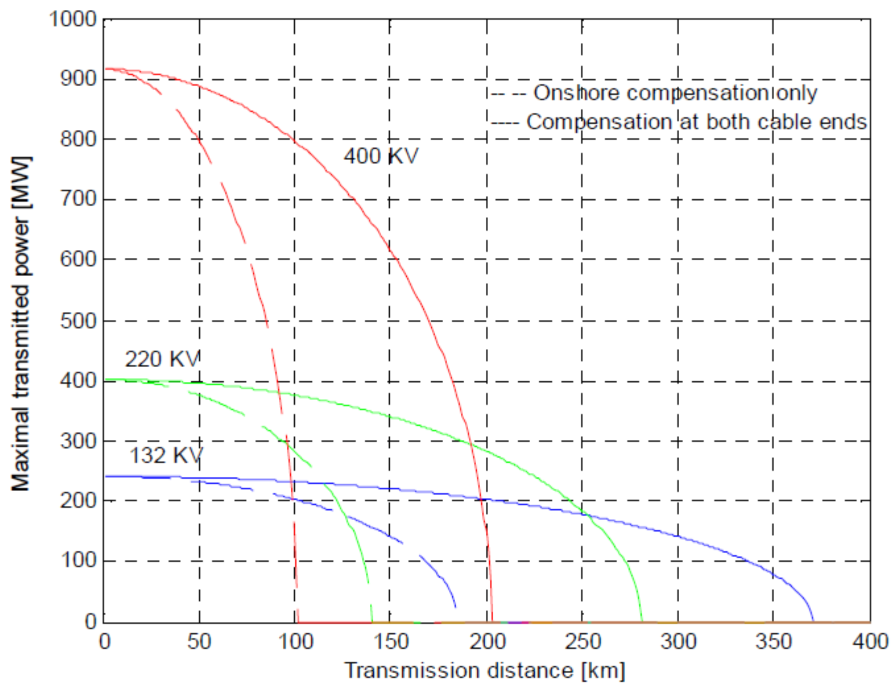


Figure 42 Limits of HVAC Cables Transmission Capacity for Three Voltage Levels, 132 kV, 220 kV, and 400 kV (Ackermann et al., 2005)

The capacity of the export cable for power transmission depends on the following parameters of a cable (Wave Energy Scotland, 2018; Ackermann et al., 2005):

- Rated voltage
- Ampacity (current carrying capacity)
- Voltage drop, or power loss, or critical distance
- Load capacity

The ampacity (current carrying capacity) is determined by the cross section of the conductor, the material of the conductor, and the ambient conditions for the cable, especially temperature. The load capacity is normally rated in MVA or MW. The transmission voltage depends on the size of the project and its distance from the shore. The power transfer limits of AC cables over long distances are 132 kV up to 250 MW and 400 kV up to 2,000 MW. 400 kV cables are only available as single core cables and require considerable amounts of reactive power compensation, limiting their use.

The HVAC export cables with rated voltages up to 245 kV are used for static subsea cables for a fixed offshore wind farm (ABS, 2012; BVG Associates, 2018). The application of HVAC export cables for dynamic subsea applications are limited (Carbon Trust, 2015; Skaare, 2017). For a FOWF, dynamic cables are needed. The design of dynamic cables connecting to FOWTs and floating offshore substations can be a challenge. Fatigue can be a design issue for dynamic cable, especially for HV export dynamic cables (Skaare, 2017).

For FOWFs, the current highest voltage AC export cable is 66 kV with project experiences in dynamic applications.

There are power-from-shore dynamic power cables used for floating oil and gas platforms, as summarized in Table 20. The dynamic cable for the Gjøa project in the North Sea is the world's first power-from-shore dynamic AC cable. An important feature of the design is the replacement of the conventional lead sheath, which is not sufficiently robust for this application, with a new innovative sheath. The Goliat project has the world's longest, most powerful dynamic AC cable. ABB has extended the technical boundaries for this, the world's second dynamic AC power-from-shore cable system. The dynamic section, which weighs 90 kg per meter and hangs in the water between the platform and the seabed, has to withstand substantial mechanical stress from currents, waves, and the movement of the platform. An important feature of the ABB solution is the innovative corrugated copper sheath that is designed to operate for the full production lifetime of the Goliat field in these extreme, high-stress conditions.

Table 20 Application of Dynamic Power Cable for Floating Oil and Gas Platform

Project	Year	Location	Distance To Shore	Water Depth	Power Capacity	Power Cable	References
Gjöa	2010	Offshore Norway	100 kilometers (62 miles)	380 meters (1,247 feet)	40 MW	ABB 115 kV AC	(ABB, 2010)
Goliat	2013	Barents Sea Norway	105 kilometers (65 miles)	400 meters (1,312 feet)	75 MW	ABB 123 kV AC	(ABB, 2013)

According to Strang-Moran and Mountassir (2018), export cables are vital for the transmission of the generated power to the grid. Up to 2018, the UK's operational offshore wind farms used 62 export cables totaling a length of 1,499 kilometers. The voltage levels of these cables range from 33 kV for nearshore wind farms without offshore substations, and up to 132 kV, 150 kV, and 220 kV for further offshore sites with one or two substations.

According to Toulotte (2020), from a geographical perspective, the potential for floating systems can be divided into two groups. The first would be in 100 meters to 200 meters of water, which would suit regions such as the Atlantic coast, the U.K., and the North Sea, while the second could be realistically designed for depths maybe five to 10 times greater. Areas such as the Mediterranean, the U.S. West Coast, and Japan, where water gets extremely deep, would require deepwater systems.

FOWF cables are subject to hydrodynamic effects induced by waves and currents, so they require sufficient mechanical strength and fatigue life of their components compared to traditional static submarine power cables. They also require high precision during the cable-laying operations, where innovative and reliable accessories also need to be handled and installed.

Toulotte (2020) pointed out the difference between the high-voltage submarine cable systems and dynamic cables and power umbilicals. The experience gained from working on numerous oil and gas fields has been expedient in developing cable and umbilical designs and perfecting manufacturing techniques. Nonetheless, there is still a technology gap that needs to be closed to efficiently carry the levels of power that the floating wind industry will require.

In oil and gas fields, when there is only a limited amount of power to transfer, very high voltages are not required. This means that medium-voltage systems are used, which have the advantage of being able to tolerate limited water or humidity ingress into the cable insulation.

Unfortunately, a lead sheath can generally not tolerate the dynamic wave movement due to fatigue cracking. The challenge is to find suitable components and designs, capable of withstanding these movements during the lifetime of the cable. An option would be to employ a manufacturing process that allows the use of different materials to form the water barrier. Proposed solutions typically include either welding or lamination with a metallic foil sandwiched between polymer layers.

The key knowledge and technology gap, however, is to understand and predict the lifetime of these components, taking into account the operational loading conditions and environment. Testing and modeling are necessary to understand fatigue, corrosion, and delamination, and this will enable the identification of materials that can resist these failure modes.

According to Carbon Trust (2018, 2020), there are gaps in the power cable system for commercial FOWFs for export cables as listed below:

- There is a lack of high voltage (130 – 250 kV) dynamic cables for export purposes, which require alternative designs compared to the static cables used in fixed offshore wind farms. To accelerate the development of high voltage dynamic cables, there are design and manufacturing challenges to overcome. In addition, handling techniques, testing, and qualification procedures and standards, condition monitoring techniques are to be developed.
- Technology development is most relevant to auxiliary components that can limit cable fatigue, particularly cable bend stiffeners, for which larger and stiffer modules may be required.

For long distance power transmission, HVDC technology is usually used. While DC flows through the whole conductor cross-section, the AC draws itself towards the conductor surface, and the middle of the conductor is not contributing to the transmission (Våben and Gudmestad, 2018). Figure 43 shows the power loss in a cable as a function of distance.

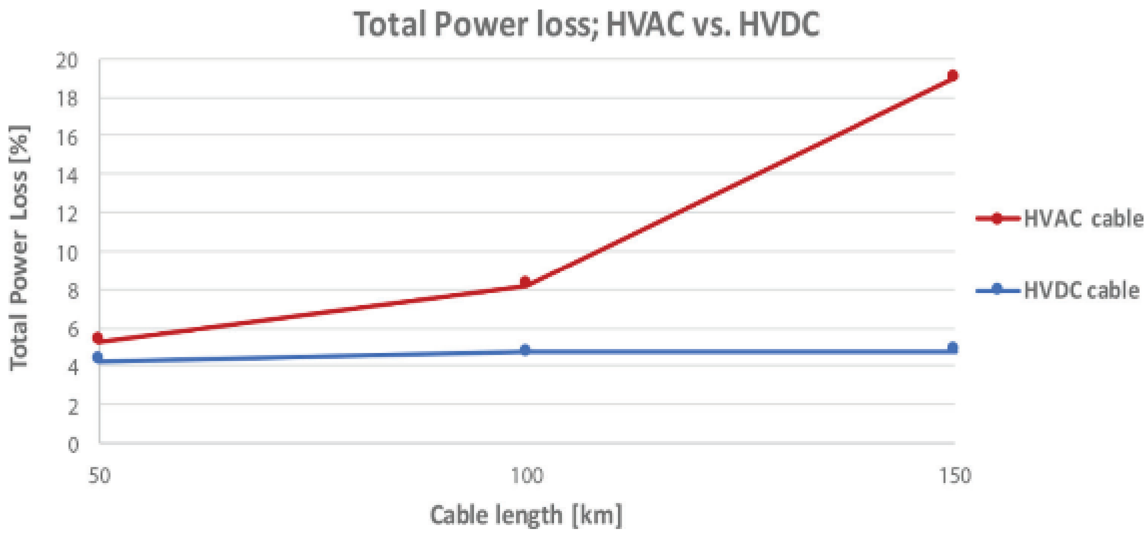


Figure 43 Total power loss in a HVAC and a HVDC system (Våben and Gudmestad, 2018)

If HVDC technology is used for the FOWF, HVDC converter stations will be needed. Dynamic subsea high voltage DC cable will be needed. However, such dynamic HVDC cables are not available on the market.

4.3.2.4 Cable Accessories

Cable accessories are important components for the power cable system. Cable accessories must be compatible with the cable and equipment connected. Accessories have static and dynamic applications, subsea, and land applications. Designs for different applications are different.

Cable accessories include cable protection systems, such as bend stiffener, bend restrictor, buoyancy modulus, etc., and cable terminators and joints.

According to Wind Power Engineering and Development (WPED) (Beesley, 2020; Orcina, n.d.), protecting power cables from excessive movement or bending is of utmost importance. High-voltage power cables are both expensive to install and replace, with replacement costs in the region of millions of dollars, even before factoring in wind turbine down-time and the huge loss of revenue from the reduced output.

Wave Energy Scotland (2018) has an overview of currently used electrical interconnection and infrastructure systems for tidal stream and wave energy projects, as well as offshore wind farms and the offshore oil and gas industry. This includes cabling and interconnection options, transformer, and switchgear requirements as well as the voltage of the various subsystems. Weerheim (2018) and Corewind (2020) also reviewed cable accessories.

A summary of different cable accessories is given in Table 21.

Table 21 Type of Cable Accessories (Skaare, 2017; Wave Energy Scotland, 2018; Corewind. 2020a)

Category	Type	Descriptions/Remark
Connectors	Dry-mate Connectors	Dry mate connectors work underwater, but connection/disconnection can only be performed in a dry atmosphere. Dry mate connectors of ratings up to 132 kV/145 kV have been used in the oil and gas industry.
	Wet-mate Connectors	Wet mate connectors can work in the subsea environment, and connection/disconnection can be performed either in a dry atmosphere or underwater. Wet mate connectors with a voltage and current rating of 30 kV and 1,300 A, respectively (approximately 67 MVA) have been used in the oil and gas industry and are commercially available.
	Joints	A cable joint or splice is a permanent connection and does not allow disconnection, but they are cheaper than either a wet-mate or dry-mate system.
Ancillary Components	Bend Stiffeners	The hydrodynamic effects of waves and currents on cables and the motions of the device can lead to substantial bending moments being applied to the termination points of a system. To protect this point from over bending and/or fatigue, bend stiffeners are utilized to increase the stiffness of the cable.
	Bend Restrictors	An alternative to a bend stiffener is a bend restrictor, which is a device to prevent the cable from over bending. Unlike a bend stiffener, it does not provide any stiffness to the internal element until it is at the 'lock-up' radius.
	Bell Mouth	Bell mouths consist of multiple cones of various diameters. Bell mouths may be used to eliminate the need for bend stiffeners or bend restrictors. However, they are less suitable for congested locations.
	Buoyancy Modules	Buoyancy modules are made of syntactic foam and consist of two main components: the internal clamp and the external buoyancy modules, which are two identical halves attached to the internal clamp.

4.3.2.5 Electrical Equipment

According to Carbon Trust (2018, 2020), commercial-scale floating substations should be feasible without significant technology development. But testing and qualification of electrical equipment is a current gap.

Equipment must be compatible with the rated voltage of the array and export cables. The equipment available to the fixed offshore wind farm can also be used in FOWFs. The differences are identified as below:

- Equipment installed on a floating substation should include dynamic effects due to the motion of the floating substation into the design.
- HVDC converter, if used on a floating substation, then dynamic subsea high voltage DC cable will be needed. However, such dynamic HVDC cables are not available on the market.
- Existing electrical equipment should be feasible with only minor modifications. But testing and qualification is a key requirement and current gap.

4.3.3 Dynamic Cable Analysis Considerations

4.3.3.1 Dynamic Power Cable Configuration

Weerheim (2018) conducted a literature review for power cables for FOWFs. The main differences between a submarine and dynamic power cables are the increased cross-sectional area of the conductor, double armoring, a friction reducing layer, and a metallic corrugated tubular sheathing (MCTS) instead of a lead sheath for improved fatigue life and flexibility.

Based on his review, the Lazy-Wave and Steep Wave hanging configurations are the most suitable for dynamic power cables. The Lazy Wave and Steep Wave configurations both use buoyancy modules. The main difference between these two configurations is the steepness at the seabed touchdown point. A Steep Wave configuration has a near vertical connection at the seabed. While a Lazy Wave configuration has a catenary shape from the buoyancy module to the touchdown point. A W-shape configuration can be used for inter-array purposes when water depths are too deep with respect to the wind turbine's distance. However, the W-shape configuration concept has not been applied to floating wind projects yet and therefore needs to be further researched and developed.

The most critical fatigue points of the common Lazy-Wave configuration are at the hang-off and touch down point. Static and dynamic bend stiffeners, as well as an Uraduct, can be used to make the cable more resistant to fatigue. The most critical component of the dynamic power cable is the metallic sheath and can be replaced by a metallic corrugated tubular sheathing (MCTS) for improved fatigue life and flexibility.

The author recommended further study of the cable, particularly, the MCTS for higher voltages, dynamic power cable damages, larger dynamic bend stiffeners, condition monitoring (CM) instruments to estimate the remaining lifetime, and fatigue analysis at water depths up to 800 meters.

According to Carbon Trust (2018, 2020), although fatigue for dynamic cable is considered a key challenge, it is believed that adequate fatigue life can be achieved by optimizing cable configurations, particularly through the use of a bend stiffener. Cable configurations must be optimized on a project-by-project basis, accounting for the cable properties, configuration (for example, lazy-wave, steep wave, catenary), motions of the floating substation, water depth, environmental conditions, and marine growth.

Rentschler et al. (2020) discussed dynamic cable configurations for dynamic inter-array cables. A hydrostatic predesign based on numerical analyses are performed to compare two umbilical shapes, namely catenary and lazy wave shape. In a parametric study, water depth and cable length are varied. As an outcome, a unique and generalized recommendation for a first umbilical design is presented.

A typical cross-section design and the mechanical properties of the cable are used for the analysis. The referenced cable with a diameter of 0.2 meters is rated at 11 kV three-phase AC with a capacity of 1 MW. A discussion of the hydrostatic parametric study is presented. In most cases, a lazy wave shape is preferable to a catenary shape.

Corewind (2020) published a review of the state-of-the-art of dynamic cable system design. The COREWIND project has selected the 66 kV dynamic power cable to further study the optimal configuration and cable fatigue performance as well as relevant requirements of cable ancillary hardware design. Critical cable parameters, including outer diameter, weight, bend stiffness, axial stiffness, and axial safe working load, are considered in the modeling of the cable. Based on the review, there are six different cable configurations for dynamic cable systems. Currently, two configurations seem to be selected for dynamic power cable design for FOWTs. These two configurations are respectively the Lazy Wave configuration and Tethered Lazy wave configuration. The selection of configurations will also depend on floating substructure types and water depth.

4.3.3.2 Dynamic Cable Analysis Methods

Eriksson et al. (2011) presented an analysis of HV dynamic power cable for the Gjøa project. The dynamic cable must allow for the platform's horizontal and vertical movement, including a lateral radius of 75 meters. To accommodate the additional length the cable requires for this, its lower part is lifted using 73 equidistant buoyancy units in what is called a lazy wave configuration (see Figure 44). An 8-meter long bend stiffener was mounted at the upper end.

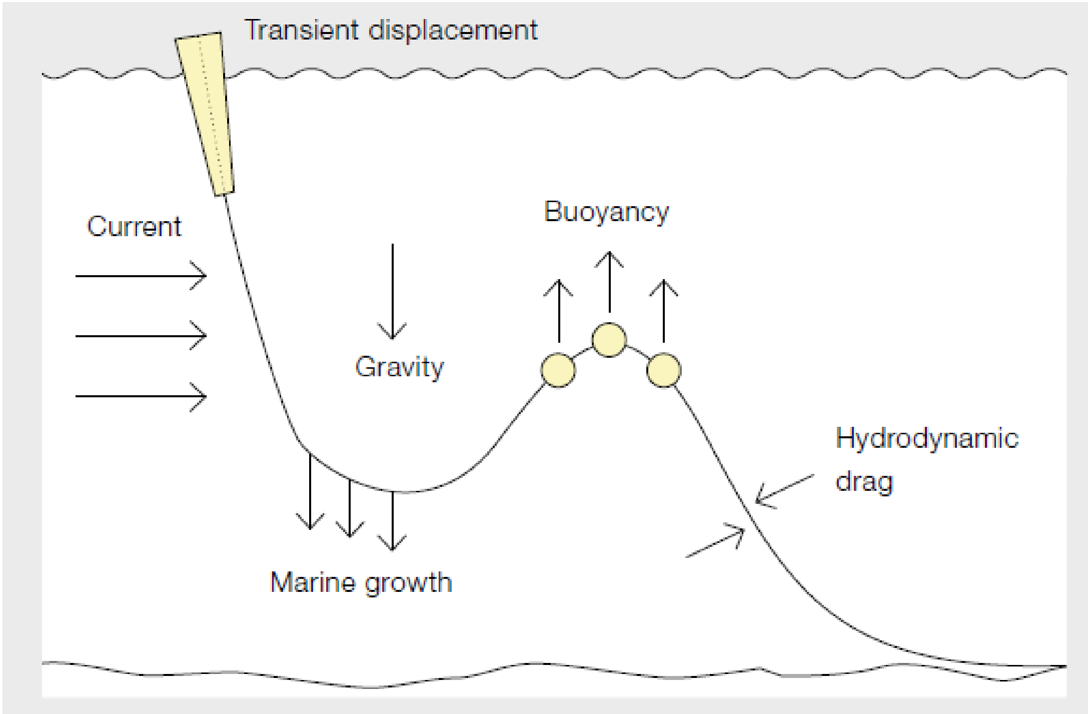


Figure 44 Factors Affecting the Mechanical Load on the Dynamic Cable (Eriksson et al., 2011)

An important part of the design process of the dynamic cable involved determining its fatigue life. This process had three main components (see Figure 45):

- Global analysis
- Local analysis and lifetime estimation
- Fatigue testing

The dynamic cable is a three-phase AC, 115 kV cable with 300 mm^2 conductors. The sheath is of corrugated copper, tungsten inert gas (TIG) welded, and double armored to prevent water ingress and withstand mechanical fatigue during its design lifetime of 35 years plus with a safety factor of six. The conductor section of the dynamic cable is larger compared to that of the static cable as the dynamic cable is thermally limited inside the bend stiffener at its upper end. The conductors are longitudinally water-sealed using a polymer compound. An optical-fiber cable with 46 single mode fibers and two multi-mode fibers is in one of the interstices. The multi-mode fibers can be used to monitor the temperature of the dynamic cable. The flexible joint connects the dynamic and static cables.

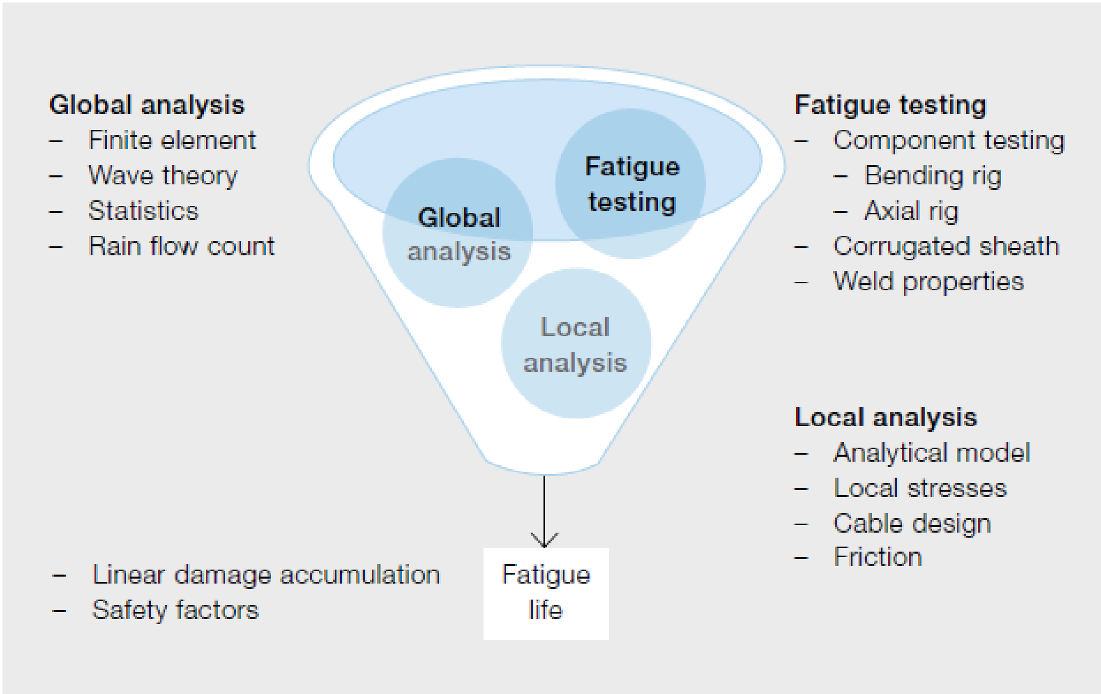


Figure 45 Conceptual Layout of Foundation in order to Determine Fatigue Life (Eriksson et al., 2011)

In the global analysis, the cable's response to translation, force, curvature, etc., is analyzed by modeling it as a one-dimensional string using global properties such as weight, diameter, axial, bending, and torsional stiffness. The configuration is optimized in an iterative procedure, selecting, for example, the position, size, and the number of buoyancy units. The axial force and curvature of the cable were analyzed under extreme environmental conditions. This analysis was accompanied by an interference analysis evaluating the possibility of collisions with neighboring risers and subsea infrastructure. Such occurrences are not permissible under any conditions.

For the local analysis and lifetime estimation, in general, there are several ways of modeling the cable on a local level. Common methods include finite element modeling and analytical models. In the case of Gjøa, a conservative analytical model was used. The strain in fatigue-critical components was calculated to be able to determine the lifetime of the cable and is dependent on several factors, including curvature and friction between helical components. Based on this analysis, the lifetime was calculated using the method of linear damage accumulation in the identified fatigue-critical components. The calculated lifetime of the cable exceeded 35 years with a safety factor of six.

The objective of the fatigue testing is to establish a Wöhler diagram (or S-N curve – a curve plotting cyclic stress against failure) of the identified fatigue-critical component. Emphasis was placed on the radial water barrier (the cable's welded copper sheath).

Various tests were performed as part of the qualification process. Among these tests, a flex test simulates the fatigue the cable will be subjected to during its lifetime by applying increased bending stresses over a shorter time. Two million cycles were applied on the full-scale dynamic submarine cable under constant axial load. The loads applied were calculated based on the global analysis. The loads occurring at the top end of the cable are more severe than at the lower end. The bending stiffener and hang-off were attached to the test section for the purpose of this test.

As the cable was to be installed with a new cable laying vessel and laying system, a sea trial was performed before the actual cable laying. The trials went well, with only slight modifications on some mechanical parts of the laying system being needed. After the sea trial, the cable was transported and installed, with the entire cable (including static and dynamic sections) was laid in one length.

After laying the dynamic cable end (including the buoyancy modules), the bending stiffener and the pull-in head and hang-off body were temporarily placed on the seabed for approximately three months before the pull-in operation. An electrical test was performed immediately after the positioning of the flexible transition joint on the seabed and installation of the buoyancy modules. Before the pull-in operation, the stored cable was raised from the seabed, and the pull-in head was secured to the platform pull-in winch wire. The pre-installed hang-off body was then raised to the hang-off table on the platform, and the cable was secured. Following the pull-in operation, the armored wires on the dynamic cable were removed, and the phase cables and optical cables were connected. The screens of the phases, and the sheath of the optical cable were connected to an earthing bar.

The project brought together knowledge and skills from two industries that are normally largely separate: the oil and gas industry and the high voltage cable industry.

Fujii et al. (2013) and Sakiyama et al. (2016) presented the development of the power transmission system for the Fukushima FORWARD project, mainly the high voltage dynamic power cable. The 22 kV inter-array cables were selected to connect the FOWTs to the floating substation, and a 66 kV export cable was selected for power transmission to the onshore station. The power cable system was designed based on both electrical and mechanical characteristics. The dynamic power cable was developed, and the following analyses were performed:

- Static behavior analysis
- Dynamic behavior analysis
- Fatigue analysis

Fugløy (2017) investigated a metallic corrugated tubular sheathing (MCTS) with respect to how various geometrical parameters, that is corrugation pitch (P), amplitude (A), sheath thickness (t), and helical inclination angle, influences the developed strain along with the corrugation geometry. The obtained results can be utilized as a parameter to predict the MCTS fatigue properties. In this thesis, the MCTS was 3D modeled and parametrized. Thereafter a finite element approach was utilized to expose the MCTS models to static axial and bending analysis and quasi-static four-point bending analysis.

Taninoki et al. (2017) presented the development of the dynamic cable for the Sakiyama 2 MW FOWT. The authors have developed a method to analyze the behavior of the cable in the sea to optimize the cable installation design and ensure long-term reliability. For the 2 MW demonstration plant, a 6.6 kV cable was used with waterproof layers provided around its XLPE insulation to simulate a 66 kV cable. The analysis method includes a selection of a cable configuration, a static analysis followed by a dynamic analysis.

Young (2018) presented the work undertaken by the Offshore Renewable Energy (ORE) Catapult to better understand the failure mechanisms of dynamic subsea cables. Cables can fail due to mechanical and electrical stresses. The next generation of dynamic cables will need to be robust enough to survive with more considerable stresses acting on them. These greater stresses will cause the cables to fatigue faster than those in a conventional static cable configuration, resulting in a greater risk of cable failure. The project will illustrate how a better understanding of these failures can create models for testing and validating cable configurations proposed for dynamic subsea applications.

This research project consists of developing models that will couple the mechanical stresses with the electrical stresses of the energized cable – the purpose of which is to provide a tool that can be used for cable health monitoring and cable failure estimation and location prediction. The desired outcome of this improved understanding of cable failure is to prevent unexpected cable faults and aid in the preparation of preventative cable maintenance. This is expected to help reach the overall goal of reducing the number of offshore cable failures, therefore reducing the cost of FOWFs.

Rentschler et al. (2019) presented a design approach for dynamic inter-array power cable based on a genetic hybrid MATLAB-OrcaFlex tool considering fatigue life, performance in extreme weather events, and economic evaluation criteria. The starting point for the dynamic analysis is cable configurations from hydrostatic optimization. Based on this hydrostatic optimization, a general design rule for lazy wave cables can be deduced in the depth range from 70 to 200 m. The fatigue analysis is based on fatigue curves and the rainflow counting method.

Thies et al. (2019a) presented the approach and applied methods for the design work that informs the development and qualification of a 66 kV submarine dynamic power cable. A lowered Lazy Wave cable configuration is chosen as the most suitable design. The numerical results form the basis for subsequent physical cable demonstration and validation tests.

The mechanical load analysis for dynamic submarine power cables is carried out in two steps:

- A global load analysis that establishes the forces and motions acting on the power cable, induced through the combined effect of the metocean environment and the aero-hydrodynamic response of the floating structure
- A local analysis that seeks to determine the local stresses (within the cross-section) of the cable, e.g., the stress the armoring or the conductor will have to withstand in operation

The global load analysis was performed with an aerodynamic-hydrodynamic coupling analysis. Several analysis runs were performed to explore the effect of different Lazy Wave configurations, incident wave direction, and wind speeds. The results show an interesting trade-off between incurred maximum effective tension and the observed bending radius. Based on the parametric analysis, a configuration was chosen for the dynamic cable. The design criteria regarding tension, compression, and minimum bending radius (MBR) constraints were met for the chosen configuration. The ability to estimate the cable response in the time domain will allow a detailed fatigue analysis, once the range of cases for the different metocean conditions is computed.

Thies et al. (2019b) assessed the mechanical performance and load parameters for an Aluminum power conductor cable. While copper is the conventional choice due to its lower resistive losses, Aluminum cores are increasingly used for static power cables, due to their benefits regarding overall cable weight and material cost. The work presented adopts a coupled aero-elastic and hydrodynamic modeling approach to simulate the behavior of the well-documented OC4 semi-sub platform, together with the 5 MW NREL wind turbine. The model allows a direct comparison between the two cable types, maintaining the overall system and environmental conditions.

The mechanical load analysis for dynamic submarine power cables is commonly carried out in two distinctive steps: global load analysis and local analysis. This paper only presents the global load analysis as an initial assessment for a 66 kV Aluminum conductor cable in a Lazy Wave configuration. The results indicate that the cable design criteria regarding tension, compression, and Minimum Bending Radius (MBR) constraints are met for the chosen configuration and the modeled selection of load cases. Based on the selected load cases, Aluminum conductor cable has the potential to contribute to a reduction of loads and cost.

Madjid (2020) presented a dynamic analysis for a power cable for the FOWT. The analysis was first performed with motion analysis, then the time-history of the motion was used for the fatigue analysis of the electrical cable based on the rainflow counting method.

4.3.4 Design Guidelines for Submarine Power Cable System in U.S.

According to Corewind (2020), until the publication of "IEC 63026 Submarine power cables with extruded insulation and their accessories for rated voltages from 6 kV (Um = 7.2 kV) up to 60 kV (Um = 72.5 kV) – Test methods and requirements" in December 2019, there is no international standard covering medium voltage (6 kV to 30 kV) submarine power cable design, manufacture, and test. Therefore, a combination of land cable and HV (>30 kV) submarine cable and umbilical standards have been applied throughout the industry.

Musial et al. (2020) presented the results of the Offshore Wind Electrical Safety Standards Harmonization workshop on electrical standards applicable to offshore wind farms in the U.S. The report can be used as interim guidelines while the formal consensus recommended practices are being developed through the AWEA/ANSI U.S. Standards Initiative.

The guidelines relevant to the submarine power cable system are summarized below:

- Workshop participants indicated that the use of an IEC standard in place of a corresponding U.S. standard is more likely to occur in the case of wind turbines that already have IEC-type certification, or for submarine cable systems, for which no U.S. standard exists, than for substations, which are project-specific, custom-designed installations.

- The terms "high," "medium," and "low" voltage are subjective and prone to misinterpretation. The terms refer to different voltage ranges in various standards and can also vary across jurisdictions. Workshop participants emphasized that when referencing a standard or procedure, it is important to verify that the range of voltages covered by that standard or procedure is appropriate.
- Submarine cables for voltages up to 60 kilovolts (kV) are covered by IEC 63026, which was recently published. (Note: IEC 63026 covers both power cables and cable accessories.)
- Existing U.S. standards apply to components of submarine cables, but there is no comprehensive U.S. standard for the entire submarine cable system. IEC standards describe methods for testing and type-certifying complete cable systems but need to be combined with Conseil International des Grands Réseaux Électriques (CIGRE) recommendations for electrical and mechanical testing of submarine cables. Acceptance of the relevant IEC standards is recommended.

4.3.5 Technical Challenges

The differences in electrical infrastructures for a fixed offshore wind farm and floating offshore wind farm are compared in Table 22.

Table 22 Electrical Infrastructures for Fixed Offshore Wind Farm and FOWF

Design Parameters	Fixed Offshore Wind Farm	FOWF	Remark
Distance to shore	Less than floating for the same offshore areas	Further from shore for the same offshore areas in deeper waters Current projects in the range of 330 meters – 140 kilometers	When FOWTs are located the same distance from shore as fixed turbines, generally the same infrastructure can be used. FOWT requires the additional equipment for dynamic cable and cable connection High voltage cable is needed for long distance power transmission FOWTs are generally located farther from shore in deeper water requiring longer high voltage cable
Water depth	Less than 60 meters	Larger than 60 meters Limited to 1,000 meters	Current BOEM call areas limit water depth to 1,100 meters
Inter-array cable	33 kV – 66 kV (AC)	33 kV – 66 kV, AC	Dynamic application is feasible with real project experiences

Design Parameters	Fixed Offshore Wind Farm	FOWF	Remark
Export cable	123 kV to 420 kV (AC)	66 kV, AC, 123 kV, AC (power-from-shore) Limited design and experiences with water depth up to 400 meters.	There is a lack of high voltage (HV) up to 220 kV dynamic export cables available on the market
Cable accessories	Cable accessories compatible to voltage of the cable are available.	Limited products and experience for dynamic application with water depth up to 400 meters.	Design of cable connectors for dynamic application could be a challenge Auxiliary components can limit cable fatigue, particularly cable bend stiffeners
HVDC technology	Mature	Not available for dynamic application	Critical length for HVAC transmission is about 100 to 150 kilometers depending on cable type (from ABB)
Equipment	Compatible equipment for 66 kV inter-array infrastructure, and high voltage export cable are available.	Limited experiences with the world's only 66 kV floating substation	Equipment includes switchgear, transformers, converters, and subsea hub

In summary, for the development of commercial FOWFs, technical challenges include:

- Equipment installed on a floating substation should include dynamic effects due to the motion of the floating substation into the design.
- HVDC converter, if used on a floating substation, then dynamic subsea high voltage DC cable will be needed. However, such dynamic HVDC cables are not available on the market.
- Existing electrical equipment should be feasible with only minor modifications. But testing and qualification procedures and standards are yet to be developed.
- For high voltage dynamic power cable, current water barrier design with a lead sheath can generally not tolerate the dynamic wave movement due to fatigue cracking. The challenge is to find suitable components and designs for water barrier with the use of different materials.
- There is a lack of high voltage (130 – 250 kV) dynamic cables for export purposes, which require alternative designs compared to the static cables used in fixed offshore wind farms. To accelerate the development of high voltage dynamic cables, there are design and manufacturing challenges to overcome. In addition, handling techniques, testing, and

qualification procedures and standards, condition monitoring techniques are to be developed.

- Auxiliary components can limit cable fatigue, particularly cable bend stiffeners, for which larger and stiffer modules may be required.
- Although fatigue for dynamic cable is considered a key challenge, it is believed that adequate fatigue life can be achieved by optimizing cable configurations. However, there are limited experiences with dynamic cable applications up to water depth up to 400 m. Further study for dynamic cable analysis and configurations in water depth up to 1,000 meters may be needed.

4.4 FABRICATION AND INSTALLATION METHODS

Based on the assessment of the fabrication and installation methods, identified technological issues include:

- Considerations for mass production in fabrication
- Onshore assembly of wind turbine and tower
- Installation methods and requirements for FOWTs

4.4.1 Fabrication Methods

Fabrication of the floating substructure should take mass fabrication into consideration. This mainly includes the following aspects:

- Design and fabrication methods should be developed for mass production
- The location and size of the assembly sites should be suitable for the size of FOWF development

Matha et al. (2017) investigated the floating-specific constraints with respect to fabrication, assembly, and installation for different floating substructure concepts for large 10 MW floating wind turbines and 500 MW wind farms. General constraints are identified, including the choice of a suitable construction site/port and the selected port's infrastructure.

4.4.1.1 Hywind

Hywind design has been developed for efficient mass production, similar to that of turbine towers and monopiles. The "Hywind Factory" methodology will be utilized to reduce costs. The "Hywind Factory" is not a physical factory, but rather a systematic approach to mature and industrialize the Hywind concept, to significantly reduce costs and improve the competitiveness of floating wind. Key focus areas of the Hywind Factory include (see Equinor, n.d.):

- Optimizing the Hywind substructure with respect to material use and production friendliness, adapting it to volume production.

- Design Hywind to be compatible with important trends in the bottom-fixed industry using standard turbines, standard installation vessels, and so forth.
- Working to standardize solutions that are common to the floating wind industry, such as mooring and anchoring and export cables.

4.4.1.2 WindFloat 1 (WF1)

For the WindFloat 1 (WF1), Cermelli, Roddier, and Weinstein (2012) discussed the project management, including local content requirements, which is a critical success factor for the project. Once fully assembled, the WindFloat cannot be transported because of its height (air draft) long distance overseas. Transportation through wet tow, therefore, should take the height (air draft) into consideration. Local fabrication and final assembly were therefore required. Roddier et al. (2017) discussed the full life cycle of the WF1 prototype.

The WF1 hull was fabricated by A. Silva Matos (ASM), a local company specializing in the fabrication of wind turbine towers. ASM expanded its business lines to operate in the Renewable Energy field, globally about 13 years ago (Principle Power, 2016b). Most of the platform columns, assembly, and outfitting were performed in a ship repair yard. The selection of the fabrication facility was strongly driven by their large dry dock, which allowed load-out of the WindFloat fully outfitted without requiring heavy lift capabilities or a submersible barge.

The columns were individually moved to a dry dock, using a 500 tons gantry crane, where the truss was fitted. The platform was outfitted in the same dry dock, including installation of secondary and tertiary steel, equipment, piping, electrical, and instrumentation. After the painting was completed, a temporary buoyancy module was fitted around each column, and the hull was moved with a 4.5m draft to a deeper dry dock for the installation of the wind turbine and integration of the overall WindFloat system. The offshore site is about 400 kilometers away from the dry dock at Setubal, South of Lisbon, where the WF1 was loaded out. The fully assembled WF1 was wet towed from Setubal to the offshore site north of Porto along the coast of Portugal at a speed of 2 to 3 knots.

4.4.1.3 VolturnUS

According to Viselli et al. (2015), the VolturnUS design is made of concrete that can be fully constructed and assembled dockside. After assembly, the entire structure is towed at a shallow transit draft with a single standard tugboat for mooring and an electrical umbilical hook up at its final installation site.

The concrete hull design, composite tower design, and construction process replicate the full-scale system. The concrete hull is constructed of 15 concrete members and representative of the full-scale design and construction process. The connections, thicknesses, and reinforcements of the concrete hull are scaled. Both the tower and concrete hull underwent structural qualification testing to confirm structural designs prior to fabrication. The assembly of the hull, tower, and turbine all took place on land at the Cianbro Modular Manufacturing Facility in Brewer, Maine.

4.4.1.4 New England Aqua Ventus I

For the New England Aqua Ventus I project, the concrete hulls are designed to be built locally. The hull will be fabricated in smaller pieces and then assembled on-site. Maine-based Cianbro will construct the modular platform segments in Brewer and barge them down the Penobscot River to Searsport, where they will be con-joined with the turbine and tower and then taken out to sea. (see Maine Public, 2020)

4.4.1.5 Full-Scale 2 MW Sakiyama Hybrid-Spar Model

Utsunomiya et al. (2015) summarized the fabrication of the full-scale 2 MW Sakiyama hybrid-spar model. The precast prestressed concrete (PC) segments were fabricated in a factory of Hume pipe at Kitakyushu city, Fukuoka prefecture. The precast segments were fabricated as a ¼ part of the circular section (outer diameter: 7.8 meters) with a height of 2 meters because of the restrictions for land transportation, as shown in Figure 46. After the accelerated curing with vapor, demolding, and air curing, the completed PC segments were transported to the construction quay at Matsuura city, Nagasaki prefecture, by using conventional truck transportation. At the same time, the steel part of the spar structure was fabricated at a shipyard.

At the construction quay in Matsuura city, four segments were joined to form a ring-shaped part with an outer diameter of 7.8 meters and a height of 2 meters in the horizontal position. The completed ring-shaped parts were then assembled together to form a circular cylinder by using post-tensioning steel bars for the bottom half of the spar structure, as shown in Figure 47.

After the completion of the PC part of the spar structure, the upper steel part was joined to the lower PC part by using a floating crane. Figure 47 shows the general view of the completed hybrid spar structure in the horizontal position.

Figure 46 Frication of Concrete Segments – Sakiyama Project

Figure 47 Concrete Part of the Hybrid Spar – Sakiyama Project

4.4.1.6 Ideol

According to Choisnet et al. (2014), the shape of the hull of the Ideol damping pool concept, with large flat panels, was chosen to ease the production process. Due to the shape of the hull, only the standard form works is required for the construction of the concrete hull, and limited bending of the rebars is needed.

Due to limited launching draught, the hull can be built not only in a dry dock but also on a quay. Construction in steel can be done by building in prefabricated blocks like any ship structure.

Choisnet et al. (2016) discussed the construction of the Ideol damping pool design concept. The main challenge in building concrete hulls is to be able to assemble and launch them. As these hulls are heavy, they cannot easily be handled. The main options offered to build a concrete hull are:

1. Build the complete hull on a quay/barge and float it off
2. Build the bottom and part of the walls, launch, then complete erection of the walls afloat
3. Build the hull up to the top of the walls on a floating dock, then complete deck afloat
4. Build the hull in modules that can be more easily transported, assemble them on either a barge or in a dry dock, and float them off

For series production, option 1 is not efficient enough. Completing afloat or building in a module are consequently the most likely options to be used on a given project. Option 2 can be interesting when access to sheltered waters for launching or a dry dock are not easily available. Option 4 will be the preferred option in deepwater ports with a large number of units being produced. The construction methods can consequently be adapted to the site under consideration.

Molins et al. (2018) explored construction options for a spar-buoy made entirely out of prestressed concrete for serial production. Prior to defining construction methods, several other prerequisites need to be established regarding worksite features and logistics were recommended:

- Construction is to take place at a coastal facility
- Facilities equipped for large-volume non-stop concrete pours
- Concrete supply
- Working around-the-clock
- Contingency plan
- Specific traveling formwork
- Optimizing form handling

In search of an appropriate solution, construction proposals based on inspiration from a variety of engineering fields: mechanized tunneling practices, far-reaching adaptations of slip-forming, reinforced centrifugal concrete pipe production, and even trenchless technologies such as pipe jacking will all serve as a basis to elaborate a series of tailored solutions.

Any given proposal is associated with a unique casting facility with singular requirements regarding space and technology. Ideally, the construction process needs to be industrialized as much as possible to standardize and speed up production, ruling out traditional formwork, which is labor-intensive and time-consuming.

4.4.1.7 Hywind Tampen

For the Hywind Tampen project, the hull will be made of concrete. The hull will be constructed vertically at a deepwater slip-forming site without upending. The Hywind Tampen fabrication sequences are listed below (Equinor, 2019):

- **First phase:** Slip-forming lower part in dry dock
- **Second phase:** Remaining slip-forming at the deepwater site (Figure 48)
- **Third phase:** Towing to the main assembly site
- **Fourth phase**: Complete substructure/tower assembly and commissioning at the main assembly site (Wergeland base Gulen)

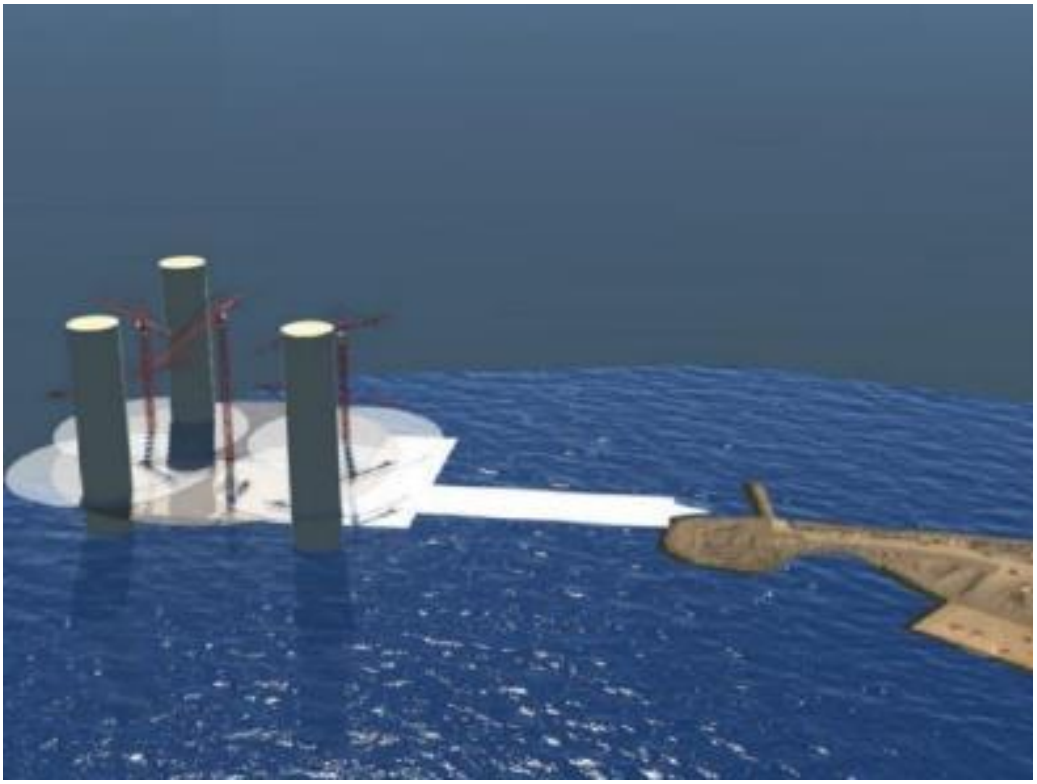


Figure 48 Hywind Tampen – Concrete Slip-forming at Deepwater Site (Equinor. 2019)

4.4.2 Onshore Assembly of Wind Turbine and Tower

Based on the current projects, the turbine components (hub, blades, and nacelle) and tower are pre-assembled before mounting on the floating substructures. For the Hywind Demo, the wind turbine and tower were partially assembled onshore, as shown in Figure 49, and for Hywind Scotland, the wind turbine and tower were fully assembled onshore, as shown in Figure 50.

Figure 49 Hywind Demo Project – Partially Assembled Wind Turbine and Tower (Statoil, 2009)

Figure 50 Hywind Scotland Project – Fully Assembled Wind Turbine and Tower (Equinor, n.d.)

Figure 51 shows the WF1 fully assembled foundation, tower, and turbine onshore before being towed offshore.

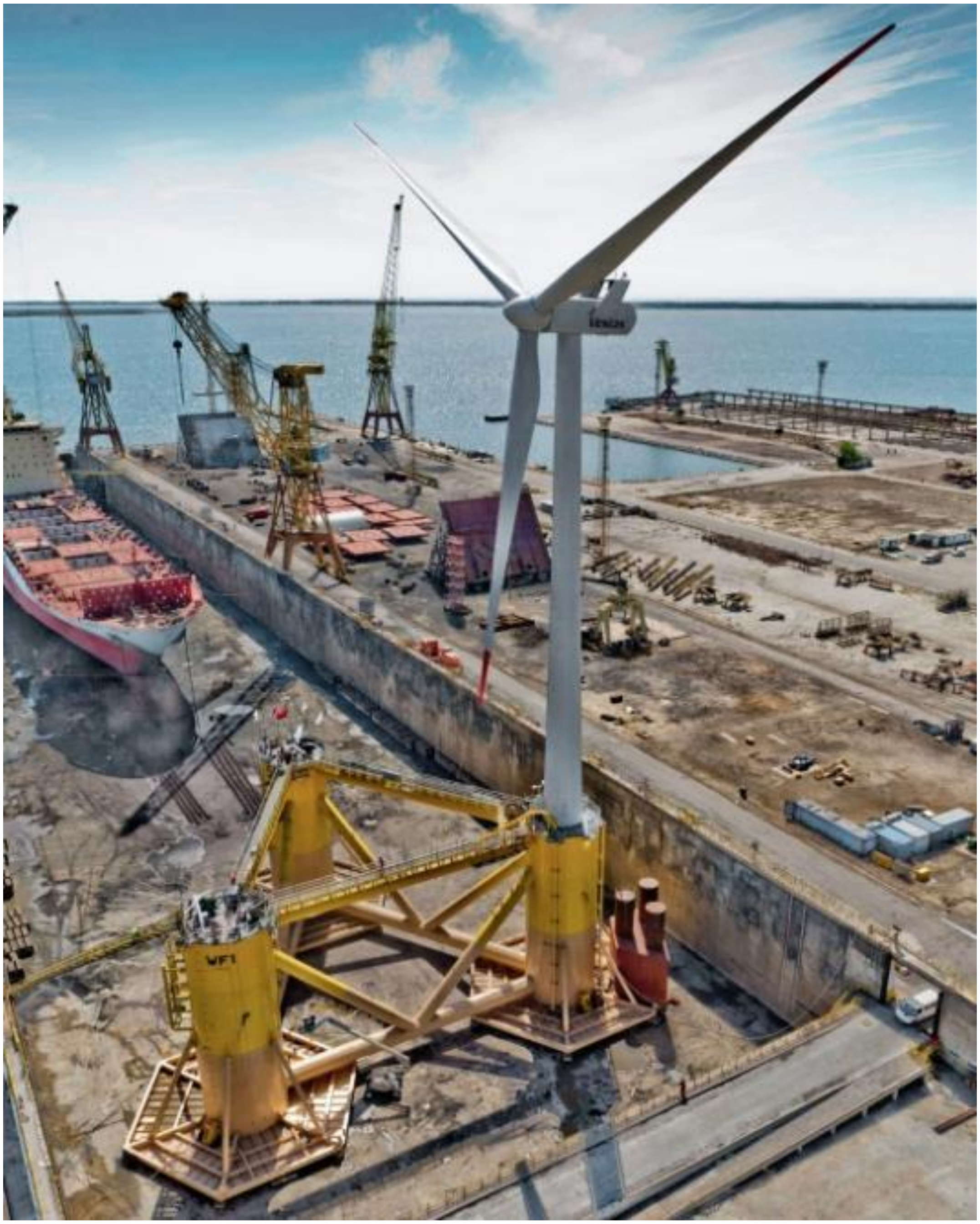


Figure 51 The WindFloat Prototype in Preparation for its Tow Offshore (ASM Industries, 2020)

4.4.3 Installation Methods

4.4.3.1 Hywind Concept

The installation of the Hywind FOWTs consists of the following steps:

- Load-out and wet tow of floating substructure (horizontal)
- Alternatively, transport of floating substructure by dry tow and float-off

- Upending of floating substructure (steel), or vertical slip-forming of floating substructure (concrete)
- Onshore assembly of wind turbine and tower
- Inshore assembly of FOWT– mounting the turbine and tower on top of floating substructure (pre-commissioning as well)
- Pre-installation of anchor and mooring system (partial mooring wet storage on the seafloor)
- Wet tow of FOWT to the offshore site (vertical upright)
- Hook-up of a mooring system
- Connection of dynamic power cable
- Offshore commissioning

For the Hywind Demo project, the turbine and tower were partially assembled and mounted on the floating substructure at an inshore location, as shown in Figure 52, before towing out to the offshore site.

Figure 52 Hywind Demo – Inshore Assembly of a FOWT (Stateoil, 2009)

For the Hywind Scotland project, the turbine and the tower were fully assembled onshore. The lifting and mating of the assembled turbine and tower to the floating substructure were performed by SAIPEM 7000. The inshore assembly is shown in Figure 53.

Figure 53 Hywind Scotland – Inshore Assembly of a FOWT (Equinor, n.d.; Technip, 2016)

4.4.3.2 WindFloat Concept

The WindFloat design allows it to be fully assembled onshore and towed to its final destination. Alternatively, the hull can be manufactured at a nearby fabrication yard, and wet or dry towed to the assembly site.

The installation of the WindFloat FOWTs consists of the following steps:

- Onshore full assembly, installation, and pre-commissioning of the turbine and substructure in a dry dock
- Alternatively, transport of floating substructure by wet tow or dry tow and float-off, inshore assembly of FOWT – mounting the turbine and tower on top of floating substructure (pre-commissioning as well)
- Pre-installation of anchor and mooring system (partial mooring wet storage on the seafloor)
- Load-out through the dry dock for onshore fully assembled FOWT
- Wet tow of the complete system to the offshore site
- Hook-up of a mooring system
- Connection of dynamic power cable

4.4.3.3 Other Concepts

For the Ideol Floatgen project (Centrale Nantes, 2017, Bayard-Lenoir, Chilard, and Swiderski, n.d.), the installation consists of the following steps:

- The concrete hull was constructed on a floating barge at quayside, as shown in Figure 54
- The barge with the concrete hull was wet towed to a dry dock
- The concrete hull was floated-off from the barge in the dry dock
- The concrete hull was wet towed to the assembly site to install the transition piece, the tower and turbine
- The anchoring system, which is made up of chains, nylon anchoring lines, buoys, and anchors, was preinstalled offshore at the SEM-REV site

- The fully assembled FOWT was towed to the offshore site to hook-up to the mooring system
- Connection of the export cable, which connects the wind turbine to the power grid onshore

Figure 54 Ideol Floatgen on a Barge at Quayside

For the SBM TLP concept, the installation is considered in the design (SBM Offshore, 2018):

- Flexibility and supply chain-based fabrication/assembly through modularity
- Assembly with standard yard means
- No dry dock required
- Limited draft allowing quayside wind turbine installation
- Wet tow with tugs

For the Stiesdal TetraSpar concept (Villaespesa, Gonzalez, and Martin, 2018), the wind turbine is installed on the floater so that the structure can be towed and installed at the chosen site as the floater has semi-submersible stability. Once it is on site, the counterweight, also called keel, is ballasted pulling down the structure and acting as a spar-buoy floating foundation.

For the Saitec SATH concept (Baita-Saavedra et al., 2020), the hull can be constructed onshore. The mooring system can be pre-laid and assembled, and FOWT can be towed to an offshore site for hook-up.

4.4.3.4 Installation of Dynamic Power Cable

The export power is pre-installed and wet storage in the seafloor. After the FOWT is hooked up to the mooring system, the dynamic cable can be installed.

For WF1 (see Cermelli, Roddier, and Weinstein, 2012), the existing export power was lifted from the seafloor, and the new 500 meters section of dynamic power cable was spliced to the export cable on the installation vessel. This operation took more than 24 hours and involved delicate operations of splicing fiber optics and high voltage terminations. The splice was contained in a watertight stainless-steel box. The splice box and new section of cable were then deployed over the stern of the installation vessel, where a cable deployment chute had been fitted to control the bending radius of the cable during deployment. Figure 55 shows the bend stiffener over the vessel stern. The cable end was then connected to a messenger line and pulled onto the floating wind turbine deck using a winch on the deck, where it was secured to a hang-off connector and was connected to the turbine switchgear and fiberoptic panel.

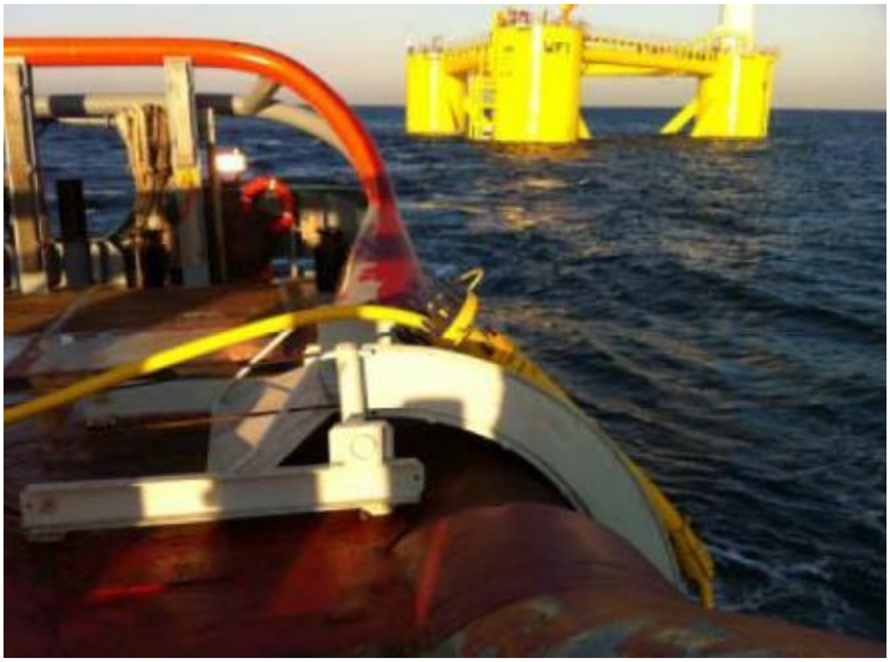


Figure 55 WindFloat 1 (WF1) – Bend Stiffener of the Power Cable over the Vessel Stern (Cermelli, Roddier, and Weinstein, 2012)

For the "Fukushima FORWARD" project, Yagihash et al. (2015) presented the dynamic cable installation. The installation process is shown in Figure 56 using the following steps:

- The 66 kV static export cable was installed
- The 66 kV dynamic export cable was connected to the floating substation
- The static and dynamic cables were connected by a submarine joint on the installation vessel
- The joint was laid down to the seabed

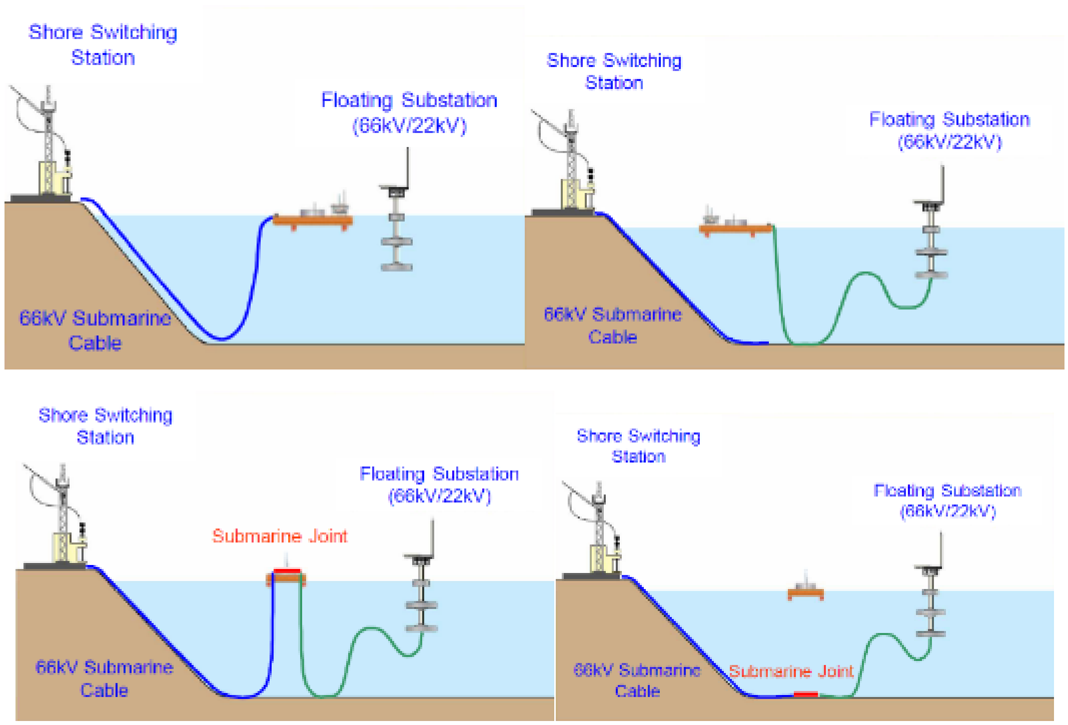


Figure 56 Installation 66 kV Static and Dynamic Export Cable – Fukushima FORWARD Project (Yagihashi et al., 2015)

4.4.4 Technological Challenges

Based on the assessment of the fabrication and installation methods, the following are found to be technological challenges:

- Design and fabrication methods should be developed for mass production.
- Fabrication and installation methods, procedures, and equipment, such as mooring connectors, dynamic cable connectors, should be standardized.

4.5 AVAILABLE FACILITIES IN THE U.S.

This section provides an assessment of the available facilities in the U.S.:

- Fabrication facilities
- Assembly facilities

4.5.1 Fabrication Facilities

Areas with potential FOWT turbine deployment and possible facilities in these areas are reviewed based on publicly available technical reports, papers mainly from BOEM, DOE, NREL California Energy Commission (CEC). NYSERDA and the Massachusetts Clean Energy Center (MassCEC). The fabrication facilities are reviewed, and the technical considerations for these facilities are also reviewed and discussed.

Fabrication facilities related to proposed FOWT projects in the U.S. are reviewed and summarized below:

For New England Aqua Ventus I project in Maine, the concrete hulls are designed to be built locally. The hull will be fabricated in smaller pieces and then assembled on-site. Maine-based Cianbro will construct the modular platform segments in Brewer (see Maine Public, 2020).

For the Redwood Coast Project (Redwood energy. 2018), based on previous WindFloat deployments, several criteria were established to successfully implement the Humboldt offshore wind project and, therefore, address the project purpose and need. Redwood Coast Energy Authority (RCEA) and Project Partners would potentially contract with one or more facilities to fabricate platform components (i.e., columns, upper beams, V-braces, lower beams, bottom plates) and to perform the final assembly (i.e., joining fabricated components and load out) of the WindFloat units. The ultimate final solution for the supply chain strategy will include a balanced approach between local development and economic power prices.

For the Castle Wind Project (Castle Wind, 2019), a detailed analysis of the actual location for the fabrication, assembly, and deployment will be developed.

The CADEMO (California Demonstration) project (Cademo, n.d.) will contribute to the development of offshore wind in California by acting as a "pathfinder" project by piloting the development, construction, installation, and operation of FOWTs on the U.S. West Coast with a demonstration project at a smaller scale to inform future larger efforts.

Keiser (2014) and Driscoll et al. (2015) summarized Budget Period 1 and Period 2 for the Hywind Maine Project proposed by Statoil in approximately 140 meters of water depth in the Gulf of Maine. Wind turbines will be manufactured at the U.S. or European plant, or a combination thereof. Individual parts will be shipped to a Maine port by sea. After delivery, they will be stored at the staging site or on a barge moored at the floating storage site until assembly. The steel substructures will require specific yard construction facilities, which a limited number of suppliers will be able to perform. Fabrication studies were carried out with two potential fabrication yards in Maine. The load-out from the fabrication yard will be by either multi-wheel trailers onto a floating barge or by a floating dock. Transportation of the substructure from the fabrication yard will be by either wet-tow or barge transport. The mooring system (chains and anchors) could be part of the substructure fabrication contract, but it is likely that all, or parts of this system, will have to be subcontracted to other companies, which may be outside of Maine.

Banister (2017) summarized the WindFloat Pacific (WFP) Project off the Coast of Oregon. Coos Bay is considered the preferred location for the WFP project. Fabrication in the U.S., preferably on the West Coast, remained the preferred scenario. Facilities at Vigor Shipyards in Portland, Oregon, part of the local supply chain, would have contributed to the construction of the project.

A general assessment of fabrication facilities related to potential wind energy areas in the U.S. are reviewed and summarized below:

Jimenez et al. (2016a, 2016b) analyzed employment and economic potential for FOWTs in Oregon. The two potential ports, Astoria, and Coos Bay, are approximately 30 kilometers to 150 kilometers from potential sites. The analysis describes the grid distance as 40 kilometers, distance to port as 90 kilometers, and water depth as 525 meters. Local content assumptions differ in each scenario. Potential wind blade manufacturers, for example, may be more likely to build a facility in Oregon if local demand for their products is greater. The proportion of manufacturing equipment that is ultimately sourced from within Oregon will depend upon global, national, and local market forces.

Jimenez et al. (2016c) analyzed the employment and economic potential for FOWTs off Hawaii's coasts. In the analysis, the grid distance is 40 kilometers, the distance to port is 40 kilometers, and the average water depth is 550 meters. Local content is determined based on input from experts with knowledge of both offshore wind and the Hawaiian economy, as well as evaluations of existing economic activity and capacity within Hawaii.

Speer et al. (2016) analyzed the employment and economic potential for large-scale deployment of FOWTs in California. In the analysis, a constant distance to the port is 80 kilometers, the distance to a grid is 67 kilometers, and the average water depth is 558. It is assumed that large equipment will be produced in California, including nacelles/drivetrains and towers. Smaller equipment is also assumed to be produced in California, along with other materials and services.

Collier (2017) analyzed the policy actions needed for offshore wind power to become an important component of California's energy mix and an economic catalyst. The floating turbines expected for California will have heights reaching as much as 700 feet, meaning that each floating turbine is effectively a giant half-ship, half-airplane, with complex manufacturing, logistical, and maintenance needs. These needs, in turn, require an extensive supply chain, ensuring that this supply chain takes root in California rather than in Asia or Europe would require major upgrades to California's infrastructure for ports, transportation, and transmission. According to the author, for the Block Island project, the nation's first commercial-scale offshore wind project, the turbine, tower, and blades were imported from Europe, while the foundation was built in Louisiana by a firm specializing in offshore oil rigs.

According to the Massachusetts Clean Energy Center (MassCEC) (2018), offshore wind development companies operating in the Massachusetts area include Bay State Wind, Deepwater Wind, and Vineyard Wind. General Electric, which is now headquartered in Massachusetts, designed and manufactured the five 6 MW turbines (GE's Power Conversion business in France (see GE. 2016) used for the first offshore farm in the United States, Block Island Wind in Rhode Island. Additionally, Massachusetts is home to two critical pieces of innovation infrastructure, the Wind Technology Testing Center, and the New Bedford Marine Commerce Terminal. Given the high transportation cost to import larger components such as towers and foundations, it is likely that some manufacturing capacity will eventually be developed in the United States.

According to American Jobs Project (2019), offshore wind can be California's next legacy-a new industry. California is home to several large capacity ports that could support offshore wind deployment with moderate investments, and full-scale offshore wind industry growth could be catalyzed by associated industries such as marine steel fabrication and composite materials manufacturing. Expertise from these industries and others could be leveraged for the offshore wind industry.

Collier et al. (2019) presented research findings on offshore wind development regarding workforce needs and policies for offshore wind and integrating offshore wind in California's grid. The first offshore wind manufacturing facility announced on the East Coast was a fixed-bottom foundation factory in Paulsboro, New Jersey, in a joint investment by a German-Chinese pipe manufacturer and wind developer Orsted.

Four types of floating platforms are studied, including Ideol's FloatGen, Principle Power's WindFloat, the Maine Aqua Ventus, and Stiesdal Offshore Technologies' TetraSpar. All companies have attempted to create platform designs that allow for serial production, streamlined logistics, and low costs.

For concrete platforms, local suppliers of reinforced concrete will be required. The platform will usually be constructed through a slipform process, in which concrete is poured into a continuously moving form to create a single structure with no joints. The process typically requires a large dock area and a hardened quay with sufficient load bearing to cope with the weight of the structures being transferred at the water's edge. Ironworkers and plasterers are typically used here, along with carpenters, operating engineers, and laborers.

For steel platforms, construction will consist of plate bending, cutting, welding, rolling, and coating. The component assembly will take place first. For steel semi-submersible designs, this category could include water entrapment plates, column shells, and steel joints before the full structure is welded together.

Many designs have adopted modular methods of fabricating and assembling the hull sections.

Then, a series of protective coatings will be applied to protect the surface against corrosion from seawater and air. Once assembled, the structure is lifted into the water by a gantry crane or slid into a dry dock for turbine assembly. While a dry dock is preferable for most designs, a slipway is also suitable. Developers prefer to avoid lifting the full platform structure because it can weigh up to 1,500 tons and require the use of heavy lift cranes, which are in short supply and thus expensive. Parts of these structures could also be constructed on an installation barge, lessening the need for dock acreage, which often is used intensively by other port clients.

Musial et al. (2019a) focused on assessing the present and future costs of FOWT deployment in the state of Oregon on a commercial scale. Considerations in study site selection include proximity to installation and service ports, proximity to land-based substations for electrical grid connection, marine protected areas, critical habitat, and habitat conservation areas, and fishing activity. The study sites' proximity to the critical infrastructure necessary for an offshore wind plant's operation and service – installation ports, service ports, and substations – was examined but did not drive the study site selection significantly. Possible installation ports that might provide slips for offshore wind power plant construction vessels and space for construction staging are summarized. The ports at Astoria and Coos Bay have depths and clearances meeting the installation requirements of wind turbines. The port at Newport is not included because of the low clearance of the Yaquina Bay Bridge. Possible service ports that might support offshore wind plant operation and maintenance are also summarized.

Musial et al. (2020a) assessed offshore wind energy resources in the Gulf of Mexico (GOM) for each of the GOM states. Three of the top four states with the highest offshore wind resource capacity are within the GOM (Louisiana, Texas, and Florida). The primary technical challenges for offshore wind turbines in the GOM are gaps around hurricane design, lower wind speeds, and lower soil strength. None of these challenges are insurmountable, but all will require some additional investment in research, development, and deployment to adapt the technology and gain the experience needed for commercial acceptance. Three sites (Port Isabel, Port Arthur, and Pensacola) were selected for detailed cost analysis.

Offshore wind projects in the U.S. are expected to heavily leverage the GOM supply chain and manufacturing facilities that already exist for oil and gas. This is especially true for projects built in the GOM, but projects built anywhere in the U.S. may use GOM supply chain facilities. An assessment of the infrastructure and supply chain was conducted by reviewing literature and interviewing regional stakeholders. The interviews indicated that large offshore spar structures for oil and gas have been fabricated with scales on the order of 427 meters (1,401 feet) in length and weighing around 45,000 metric tons, many times larger than an offshore wind substructure. The steel rollers used to fabricate these structures are capable of rolling steel 11 centimeters thick into 26 meters (85 feet) diameter cans, which could be adapted for rolling steel turbine towers. However, the steel rollers are not currently capable of producing a tapered cylinder but would still be useful for offshore wind applications. At the current scale of the substructure and tower components, manufacturing facilities in the GOM are easily capable of meeting the size requirements for the offshore wind support structures, but the current volume of production at most facilities may be too slow for large offshore wind energy projects. It is estimated that fabricating these types of substructures may be limited to 2–3 units per month (estimate assuming a jacket substructure), which would be insufficient for offshore wind project installation timing, assuming 600 MW scale developments. Because there is no simple solution to increase production volumes, investments in faster plant through-put should be investigated to meet future demand as industry demand increases.

Further research is needed to assess the impacts of tariffs on importing of steel, which is the major material comprising a wind turbine. Steel tariffs have been cited as a barrier to establishing new factories to manufacture extra-large monopiles, which are now made exclusively in European factories.

Musial et al. (2020b) provided cost, technological, and resource data for floating offshore wind technology deployment at a hypothetical reference site representative of conditions in the Gulf of Maine. This study focuses on the Aqua Ventus technology developed at the University of Maine (UMaine) over the past decade, which recognized that new offshore floating wind technology was needed to harness the state's predominantly deepwater offshore wind resource. Compared to a steel substructure, the concrete base material of a semi-submersible enables both the local fabrication and increased tolerance to the corrosive environment at sea. The platform's shallow water draft and stable base enable quayside assembly and service, as well as load-out to an ocean-based station with minimal dependence on heavy-lift installation vessels.

Based on the above review, for modularized design, the components used for assembly can be manufactured at an onshore fabrication yard or a factory, while the components can be transported over land from the fabrication yards. Fabrication facilities for components are widely available across the U.S. Wind turbines can be manufactured at the U.S. or European plant, or a combination thereof. Facilities currently used for onshore and fixed offshore wind turbines and oil and gas platforms can be used and refurbished to manufacture the tower and hull components of the floating substructure as well.

However, if the hull components are large, moving these components using land transportation can be difficult. It is preferred that fabrication is performed locally. Thus, the fabrication yard should be near or be part of the assembly yard close to the port, which is similar to the use of a shipyard to build a ship and subsequently load-out the ship. Manufacturing capacity of larger components such as towers and floating substructures is likely to be eventually developed in the United States. Facilities currently used for onshore and fixed offshore wind turbines and oil and gas platforms can be used and refurbished to manufacture the floating substructures as well. There may be limitations of fabrication speed for commercial size FOWFs to increase production volumes; investments in faster plant through-put should be investigated to meet future demand as industry demand increases.

4.5.2 Assembly Facilities

FOWTs can be fully assembled onshore and in-shore. An assembly yard near the port and a port suitable for in-shore assembly will be needed as assembly facilities. To load-out the assembled FOWTs, for example, the WF1 project required a dry dock for load-out before wet tow to the offshore site for offshore installation. For a spar-type FOWTs, such as Hywind, a deepwater site for assembly is needed.

Assembly facilities related to proposed FOWT projects in the U.S. are reviewed and summarized below:

For the New England Aqua Ventus I project, the concrete hulls will be conjoined with the turbine and tower at Searsport, and then taken out to sea (Maine Public, 2020).

For the Redwood Coast Project (Redwood Energy, 2018), the project, including the turbine, will be assembled and tested onshore or quayside in a controlled environment. No heavy lift operations or commissioning of the turbines will be conducted at sea. As a result, transport and installation of the project are simplified, require less costly vessels, and are not subject to the same weather restrictions as offshore wind projects employing bottom-fixed foundations.

Infrastructure planning, in conjunction with the Port of Humboldt Bay, is already underway. The Project Partners plan for facilities at the Port of Humboldt Bay to potentially serve as the final assembly, hull load-out, turbine installation, and future maintenance base for WindFloat units. As a result, the Redwood Coast Project would require investment and revitalization of local infrastructure at the Port of Humboldt Bay and other nearby onshore facilities. To the greatest extent possible, the

Redwood Coast Project will maximize the use of existing facilities and collaborate with local stakeholders to identify and address local infrastructure improvements.

For the Castle Wind Project (Castle Wind, 2019), the preliminary analysis indicated that ports of Hueneme, California (Oxnard), and Long Beach, California, could have the necessary capabilities for the assembly and deployment of the FOWTs. Though the Port of Morro Bay does not have an adequate staging area for the FOWT assembly and deployment, Castle Wind has committed to set-up its maintenance facility at the Morro Bay harbor.

Keiser (2014) and Driscoll et al. (2015) summarized Budget Period 1 and Period 2 for the Hywind Maine Project. Based on the proposed plan, the assembly work will be performed at two different locations: (1) an onshore area with a port facility that will be used for storage of wind turbine components and assembly of the rotor ("onshore assembly site"); and (2) an inshore area that will be used for the upending, ballasting, wind turbine erection and completion work ("inshore assembly site") (See illustration in Figure 57). In addition, two storage areas will be required to store components before assembly and assembled units prior to tow to the site. The base case onshore assembly site is the Sprague Terminal at Mack Point. The base case inshore assembly site, chosen to accommodate the substructure during upending, ballasting, and wind turbine erection, is located in Penobscot Bay east of Islesboro Island. However, the ultimate suitability of this site location is uncertain based upon the findings from the bathymetry surveys undertaken in 2013.

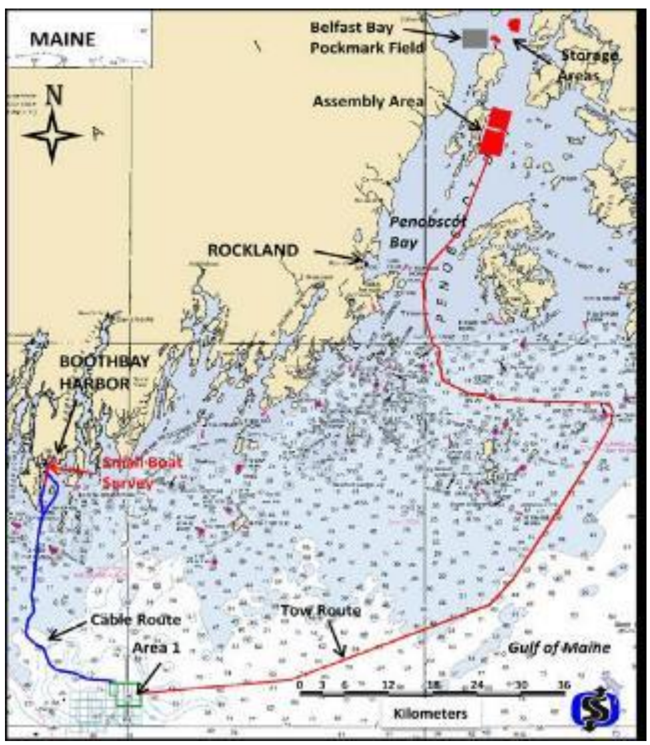


Figure 57 Post-survey Location Map (Keiser, 2014)

To allow for storage of the fabricated but not upended substructures and other project equipment, two designated areas were identified as storage areas. These areas are located north of Isleboro, with a water depth of 10 – 40 meters. The areas are planned to be used for storage of the substructures before upending and for temporary mooring of vessels/barges involved in the marine operations, etc. In the event the assembly area is relocated, it may be necessary to reassess the suitability of the proposed storage area, as well.

Prior to towing the assembled units to the offshore site, the assembled units may be moored. The temporary inshore mooring location initially selected (but under re-evaluation after tow-route bathymetric survey) is south of the inshore assembly site. At these temporary moorings, commissioning work could also be executed so that the assembly barge could be used as efficiently as possible.

For port selection, the channel depth, degree of shelter, and unrestricted access to the offshore resource area are considered. In practice, suitability will depend on a number of other considerations, including but not limited to existing infrastructure (alternatively, required upgrades), vertical/horizontal clearance limits, and competing port uses.

For sheltered inshore assembly areas, three potentially suitable locations are identified based on an inspection of the spatial characteristics, including water depth, a viable transit path to open water, and benign environmental conditions during the construction season (e.g., wind, wave, current). These locations include the Atlantic inshore assembly area in Penobscot Bay, the South Pacific inshore assembly area behind the Channel Islands, and the North Pacific inshore assembly area in the Strait of Juan de Fuca. The ports within 500 kilometers radius around each of the three inshore assembly areas are also shown. Statoil has stated that this is a reasonable limit for a project using a vertical-tow installation strategy.

For the WindFloat Pacific (WFP) Project, according to Banister (2017), over the course of the project, Principle Power (PPI) determined that facilities in Coos Bay were less capable of supporting the turbine installation sequence than others in the region. In their place, PPI determined that the turbines would be installed in the Port of Astoria, at the mouth of the Columbia River. While some upgrades would be required, such as load-bearing capacity, the Port of Astoria has the space for laydown of turbine assemblage, and the infrastructure is sufficient to accommodate the land shore turbine crane needed to perform the heavy lifts and ballasting operations. After turbine installation, the WindFloats, with the turbines mounted, would be towed from Astoria directly to the offshore lease site. PPI intended to use the Port of Coos Bay as the shore-based headquarters for Operations and Maintenance (O&M) and procurement activities, such as receiving mooring and electrical cable components.

A general assessment of assembly facilities related to potential wind energy areas in the U.S. are reviewed and summarized below:

Elkinton et al. (2014) carried out a review of the capability of U.S. ports to support offshore wind project development and an assessment of the challenges and opportunities related to upgrading the capability to support the growth of offshore wind installed in U.S. waters by 2030. The report and the open-access web-based Ports Assessment Tool resulting from this study will aid decision-makers in making informed decisions regarding the choice of ports for specific offshore projects, and the types of investments that would be required to make individual port facilities suitable to serve offshore wind manufacturing, installation and/or operations. In this study, the logistical requirements of offshore wind ports to service offshore wind were identified. This review was based on lessons learned through industry practice in Northern Europe. A web-based port readiness assessment tool was developed to allow a capability gap analysis to be conducted on existing port facilities based on the identified requirements.

To facilitate a more in-depth infrastructure analysis, six ports from different geographic regions in the U.S., including North Atlantic, South Atlantic, Gulf of Mexico, Pacific, and Great Lakes, were evaluated. Commonalities, trends, and specific examples from these case studies are presented and provide a summary of the state of offshore wind port readiness in the U.S. and illustrates the direction some ports have chosen to take to prepare for offshore wind projects. As a result, most U.S. ports will likely require soil strength improvements before they can fully support offshore wind project construction.

BVG Associates (2018) carried out a review of Virginia ports and associated opportunities relating to offshore wind and an evaluation of the strategic fit with the current and future supply chain. This report outlines the benefits of a collaborative multistate cluster concept, envisaging a "Mid and South Atlantic Coast supply cluster." The report includes a review of eleven high potential facilities. While each of these ports shows great potential for offshore wind use, the offshore industry requires very specialized facilities with special attributes. Each of the port facilities highlighted will require some upgrades or modifications to meet offshore wind requirements. This report provides details of the required upgrades specific to each activity at each port. The two Cape Charles Harbor facilities and two of Virginia's Port Authority properties, the Newport News Marine Terminal (NNMT) and the Portsmouth Marine Terminal (PMT), show promise for future offshore wind use.

According to American Jobs Project (2019), if California seeks to achieve large-scale offshore wind development, the state must make investments in its port and harbor facilities to support the assembly, staging, fabrication, and construction of turbine components. Globally, ports are the nucleus of offshore wind development and play a unique role in the cost reduction and efficiency of offshore wind projects. In this fast-growing industry, ports are required to facilitate ever-larger turbine components, bigger vessels, and an increased number of activities that span the entire life cycle of an offshore wind project, from assembly and operations and maintenance (O&M) to decommissioning. Wind turbine capacity will increase beyond 10 MW, and rotor diameters will reach sizes over 650 feet by the early 2020s; therefore, offshore wind ports will need to have adequate capacity to support the handling of these components. Because they are increasingly becoming sites for industry resources such as manufacturing warehouses, testing facilities, and training centers, ports are a natural focal point for offshore wind knowledge, labor, and capital.

California's ports are the largest on the West Coast and provide the state with a competitive advantage due to assets such as access to deep water and available space for new facilities. However, continued port planning and upgrades will be required to support the evolving needs of the offshore wind industry. As offshore wind technology becomes more advanced and turbine components become larger, California will need to address logistical challenges through a multipronged, years-long effort that targets several components of port operations, including material handling capacity, innovation, safety training, and workforce development. This effort will require port officials and state and local leaders to work together to identify port needs and assess possible funding mechanisms. It will also require regular dredging from the U.S. Army Corps of Engineers to maintain the federal navigation channel and improve navigation channel depths and widths. Many ports will require navigational aids such as physical and electronic buoys and regular surveys of navigation routes to ensure safe passage. Investing funds to increase load-bearing capacity and provide other site improvements at port and harbor facilities could have a ripple effect across other sectors, leading to economic revitalization in communities along California's coast.

In the BOEM call areas, ports are the focal point of activity and will require funds for capacity upgrades. The Port of Humboldt Bay is the only deepwater port north of San Francisco that can facilitate access to wind speeds above ten meters per second and has hundreds of acres of vacant industrial space to support dockside turbine assembly, making the port a strategic advantage for California's offshore wind industry. Access has improved due to roadwork on Highway 299, but the port will require quayside upgrades and continued dredging to support the assembly and towing of offshore wind components (American Jobs Project, 2019). Although the Port of Morro Bay has limited capacity to support the staging and transportation of heavy turbine components, the port is similarly well located to facilitate offshore wind development on the central coast of California. In addition to capacity upgrades, enabling firms in the value chain to co-locate near these ports can streamline offshore wind activity and innovation, as seen in the impact of recent investments at the Port of Taichung (American Jobs Project, 2019).

Not only is proximity to the port a key consideration for business, but proximity to research and innovation is a key factor in where offshore wind firms locate. Innovation districts are geographic areas where anchor institutions and companies cluster, connecting with startups, incubators, and accelerators.

California is home to eleven major ports that are dotted along the state's diverse coastline. The report presents a few case studies, including growing an industry cluster at the Port of Taichung, establishing an innovation district at the Port of Rotterdam, and empowering local communities in New Jersey.

Collier et al. (2019) presented research findings on offshore wind development regarding workforce needs and policies for offshore wind and integrating offshore wind in California's grid.

California is the nation's fourth-largest wind power generator, but its wind supply chain is negligible. The state has no factories manufacturing large-size blades, nacelles, or towers, and it produces only a small share of other wind components. The large offshore blades, which reach up to 300 feet long, cannot be transported on existing highways or rail lines and can only be delivered by ship from a manufacturer located at the quayside. For California offshore wind, turbine factories in Iowa or Colorado will not suffice. Either these huge, complex components will need to be imported across the ocean from offshore manufacturers at seaports in Europe or East Asia, or factories must be constructed at California's own ports.

The first major supply chain component that needs to be located in California is likely floating platforms because their bulk makes them hard to transport. The state would benefit from taking a proactive stance in working with industry to identify and develop possible port locations, possibly a multi-site network including Humboldt Bay, and support the development of other infrastructure such as long-distance transmission lines.

Musial et al. (2019a) summarized a few ports along the Oregon coastline that could be used as installation or service ports. The ports at Astoria and Coos Bay have depths and clearances meeting the installation requirements of wind turbines.

According to Musial et al. (2019b), developers and state bodies have started to make investments in port infrastructure to ensure there are sufficient cranes and laydown space required for large-scale commercial projects. There are ports in the United States that are potentially suitable for offshore wind construction, staging, and assembly. The few ports that have made recent infrastructure investments to upgrade and prepare for the first wave of projects are Port of New Bedford (Massachusetts), Brayton Point (Massachusetts), New London (Connecticut), and Tradepoint Atlantic (Formerly Sparrow Point) (Maryland). Vineyard Wind leased the New Bedford Commerce Terminal for 18 months as the primary staging and deployment base for its 800-MW project.

The development and timing of port infrastructure could become a significant bottleneck for the industry. This may be especially true as wind turbines, and project sizes continue to grow and put a strain on the capacity of existing infrastructure in terms of heavy lifting, ship access, clearances, channel draft, and physical laydown space.

NYSERDA (2019) presented the 2018 Ports Study on the assessment of ports and infrastructure for the New York State in support of the New York State Offshore Wind Master Plan. Waterfront facilities play a critical role in all phases of offshore wind farms. Many large, heavy offshore wind components, such as nacelles, blades, and foundations, can only be transported by water. Facilities will be needed to serve as installation and staging areas where components can be accumulated prior to being loaded onto the installation vessels and transported offshore.

The Unrestricted Air Draft Facilities Alternatives Assessment is one of the collection studies prepared on behalf of New York State as a part of the 2018 Ports Study. Air draft, which is the vertical clearance between the water's surface and the maximum height above the water due to a restriction such as a bridge, utility line, or airport glide slope, can provide logistical constraints at a port and along the installation vessel routes that impact the transportation and staging of both components as well as the vessels themselves. The objective of the Unrestricted Air Draft Unrestricted Facilities is to identify additional New York facilities, not subject to air draft restrictions, which may potentially be used as staging and installation facilities to support the development of offshore wind in the greater New York area and complement sites in other areas of the state and region.

The Offshore Wind Operations and Maintenance (O&M) Port Facilities Siting Catalog is one of a series of reports prepared on behalf of New York State as a part of the 2018 Ports Study. The objective of the 2018 study is to determine typical site characteristics of facilities intended to support

O&M vessels and highlight several waterfront sites in the state that may potentially serve as O&M facilities through the service lifetime of offshore wind farms.

The objective of the 2018 study is to identify the facilities with the greatest feasibility for offshore wind use and develop concept designs of those facilities in order to illustrate their potential while also developing a deeper understanding of activities, schedules, and costs required to develop each facility.

The report includes a detailed assessment with Pre-front End Engineering Design (Pre-FEED) on the following ports selected by NYSERDA, based on significant stakeholder input, and a combination of site characterization information provided by the terminal operator, publicly available information, and exploratory geotechnical investigation program completed for NYSERDA:

- Port of Albany-Rensselaer
- Port of Coeymans
- Port Ivory
- South Brooklyn Marine Terminal (SMBT)

The Port of Albany consists of multiple facilities, both on the western bank of the Hudson River, in Albany, New York, and on the eastern bank of the Hudson River in Rensselaer, New York. This site may potentially support manufacturing and fabrication activities; for example, this may include manufacturing of nacelles, towers, or blades, foundation fabrication, or substation fabrication activities.

The Port of Coeymans site is located along the west bank of the Hudson River in Coeymans, NY, north of the Mid-Hudson Bridge. The Port of Coeymans, which is a privately owned and operated marine terminal, is a subsidiary of Carver Companies. The site may potentially support manufacturing and fabrication activities; for example, this may include manufacturing of nacelles, towers, or blades, foundation fabrication, or substation fabrication activities.

Port Ivory is located in the northwestern corner of Staten Island, NY, along the Arthur Kill Federal Channel and northwest of the Goethals Bridge and generally refers to the area formerly occupied by the Ivory Soap factory. The Port Ivory site, in general, can be characterized as undeveloped. Therefore, all new infrastructure will be necessary in order to support offshore wind operations.

The SBMT Pre-FEED is approximately 63 acres of the total 88-acre site area is proposed for offshore wind. The site may potentially support staging and installation activities or manufacturing and fabrication activities, which would potentially include receiving, storing, outfitting, and load out of components onto a transportation or installation vessel; fabricating foundation or offshore electrical service platform components; or manufacturing nacelles, towers, or blades.

Musial et al. (2020a) assessed offshore wind infrastructure in the Gulf of Mexico Offshore (GOM). The port's infrastructure in the GOM is generally well equipped to support the renewable offshore wind industry because the desired port characteristics for oil and gas are similar to those for offshore wind. The ports on the coast of Texas and Louisiana serve as the primary manufacturing and operational ports for offshore energy projects. These ports are not only equipped with quayside high-capacity cranes to lift large components from the fabrication facilities but are placed in protected waters shielded from undesired metocean conditions. Many ports also offer easy vessel access with limited overhead clearance issues and shallow draft restrictions. A few of the ports are equipped with dry docks that may be adapted for floating offshore wind substructure fabrication and load-out to on-site construction sites and operations and maintenance projects.

The oil and gas industry inventory includes several heavy lift offshore jack-up vessels with large crane capacities (>1,000/ton). However, offshore wind projects require the ability to lift heavy components to higher elevations (hub heights increasing up to 140 meters (459 feet) or greater). This height requirement is unique for the installation of wind turbine nacelles weighing over 500 tons and requires purpose-built turbine installation vessels that do not currently exist in the U.S. fleet.

For FOWTs, the GOM may use the already existing port infrastructure and heavy-lift crane capabilities to erect the turbines at the quayside and float the turbines out to the site using a US-flagged tug. Significant investment is needed in repurposing or building a new fleet of offshore wind turbine installation vessels.

The industry stakeholder interviews also identified over a half-dozen large-scale organizations located within the GOM region that may have capabilities to support the offshore renewable energy industry. These organizations primarily consist of engineering, procurement, construction, and installation (EPCI) contractors and shipbuilders. These EPCI organizations have a history of successfully installing complex offshore energy projects and are willing to take on the challenges and opportunities of the offshore wind industry. The shipbuilding yards may also be able to contribute their skilled labor and specialty tooling that could be adapted for the fabrication of floating offshore structures. These interviews were limited in scope. A list of shipbuilding yards is presented and is believed to be a small fraction of the capabilities that exist in the GOM region, and that may be brought to bear on the U.S. offshore wind industry.

The GOM is generally better outfitted than other parts of the country, but there are several areas where investment is needed to close gaps and adapt the supply chain to meet the needs of the offshore industry. In doing so, these investments can potentially re-establish the GOM as an industrial center for a new offshore wind economy. Potential benefits could come from not just offshore wind power plants installed locally but from economic activity associated with near-term production in the northeastern U.S. and other offshore regions of the world.

Schatz Energy Research Center (2020) presented studies conducted on port and coastal infrastructure requirements, constraints, and opportunities for the California north coast. Considerations for assembly port include sufficient space, area dependent on navigation constraints, ground improvements. Port upgrades include dredging a wider entrance channel, a new pier that can handle heavy loads, berth dredging, and yard ground improvement.

Based on the above review, it appears that there are sufficient ports in the U.S. in terms of quantity and locations in the potential wind energy areas. However, there are limitations in terms of water depth, air draft, and space. Most of these ports may need upgrades to strengthen soil bearing capacities, a new pier and wharf to handle heavy loads, an increased heavy lifting capacity, and a modification to the navigation channel for unrestricted access.

4.5.3 Technological Challenges

The requirements for the fabrication and installation are to allow mass production.

For the fabrication facilities, two options can be considered:

- **Option 1:** for modularized design, the fabrication facilities can be anywhere across the U.S. The components can be transported through the land to the assembly yard.
- **Option 2:** for large components, the floating substructures can be fabricated near the assembly yard, or the fabrication facilities can be part of the assembly yard. This is similar to a shipyard that builds and loads-out ships.

In addition, the requirements for assembly yards and ports are summarized in Table 23.

Table 23 Requirements for Assembly Yard and Port

Installation Stage	Assembly Yard (Onshore)	Assembly Port (Or Quay/Dock)
Load-out	Near port Or part of the port	Equipped with load-out area, such as dry dock, or slipway
Wet tow (from loud-out location to port)	Near port Or part of the port	Minimum water depth 5-10 meters Transit path clearance
Up-ending **Vertical slip-forming (concrete)**	Near port Or part of the port	Water depth: • Spar-type: 80-120 meters • Other types: not applicable
Onshore Assembly of Wind Turbine and Tower	Work and storage areas Heavy lift equipment	Optional
Mounting turbine and tower on floating substructure (inshore assembly quayside)	Near port Or part of the port Heavy lift equipment	Water depth: • Spar-type: 80-120 meters • Other types: 10-20 meters • Heavy lift equipment
Wet tow (from port to offshore site)	Near port Or part of the port	Water depth • Clearance • Draft and air draft • Transit path to open water

From this assessment, technological challenges include:

- Fabrication facilities are available across the US. Existing facilities used for onshore and fixed offshore wind turbines, and oil and gas platforms can be upgraded to manufacture the floating substructures. Components for FOWTs may not be available locally. However, these can also be transported across states or imported from other countries in Europe and Asia.

- Assembly yards and assembly ports are needed for the assembly of FOWTs the size of the assembly yard, the port, and the water depth of the port should be suitable for the size of the FOWF to be developed. The assembly facilities should take mass production into consideration. Both draft and air draft of the FOWTs should be considered in the assembly port and transit route for wet tow.
- There is a need for assembly yards and ports for FOWT commercial projects. Current assembly facilities and ports may not meet the requirements for mass production and installation. It is recommended that a more detailed survey be performed for assembly yards and ports. When necessary, these yards and ports may need to be upgraded and expanded.

4.6 CURRENT MODELING EFFORTS

The current modeling efforts including:

- Integrated analysis
- Computational Fluid Dynamics (CFD)
- New methods under development

4.6.1 Integrated Analysis

4.6.1.1 Project Experiences

The current standard practice in the design of FOWTs is based on the integrated analysis. The available integrated analysis software or programs applied for different design concepts of FOWTs are summarized in Table 24.

Table 24 Integrated Analysis Software

Program	Developer	Description	Applications
ADAMS and FAST	MSC NREL	An aero-hydro-servo-mooring integrated dynamic analysis tool based on a commercially available multibody-dynamics solver (MBS), MSC.Adams and NREL/FAST.	Toda Hybrid Spar
AQWA coupled to PHATAS	ANSYS ECN	PHATAS is a time domain (TD) wind turbine simulation tool developed by ECN, which includes rotor aerodynamics, rotor and tower structural dynamics, drive train dynamics, and the turbine control system. Ansys AQWA is a commercial suite of hydrodynamic programs. Two programs are coupled through a PHATAS DLL link to Ansys AQWA.	GustoMSC Tri-Floater
DeepLines Wind	Principia	DeepLines Wind is a fully coupled aero-hydro-servo-elastic program designed specifically to assess the dynamic response of floating and fixed-bottom wind turbines submitted to offshore environmental loadings.	SBM TLP
FAST	NREL	FAST is a coupled multi-physics engineering tool that can model wind and wave inflow fields; rotor aerodynamics; platform and mooring hydrostatics/dynamics; structural dynamics of the blades, drivetrain, tower, and substructure; and controls of offshore wind turbines.	Hywind Demo VolturnUS
OpenFAST	NREL	Open-source engineering tool developed from FAST for FOWTs coupled analysis.	TetraSpar
OrcaFAST	NREL Orcina	OrcaFAST is a combination of OrcaFlex and FAST which is connected through FASTLINK. OrcaFlex is a software package for the dynamic analysis of offshore marine systems.	WindFloat 1 (WF1) Ideol Floatgen
SIMA	Marintek	SIMA is a collective term for several Marintek software programs, including SIMO and Riflex, with aero-elastic modeling of the turbine and tower, developed with a common graphical user interface for simplified modeling, simulation, and post processing.	Hywind

Huijs et al. (2014) performed numerical verification of the GustoMSC Tri-Floater semi-submersible equipped with the NREL 5MW reference wind turbine. Aero-hydro-servo-elastic simulations have been performed using Ansys AQWA coupled to PHATAS. Based on the simulation results, it is concluded that the Tri-Floater design meets the requirements regarding motions, accelerations, and mooring loads. Furthermore, it is shown that uncoupled frequency domain analysis can be applied to assess the wave frequency component of the global motion response in early design stages, where computationally demanding coupled analyses are less practical.

Viselli et al. (2015) presented the prototype measurement for the VolturnUS floating wind turbine. Some representative data for the VolturnUS 1:8 floating wind turbine are provided in this paper. These data are compared against a numerical representation of the 1:8-scale physical model for the purposes of numerical code validation. The results of coupled aeroelastic-hydrodynamic numerical modeling software FAST were validated against experimental results. The numerical model results compare favorably with data collected from the physical model.

Driscoll et al. (2016) performed an integrated Hywind Demo FOWT using the NREL's FAST simulation tool. Measured wind speeds and wave spectra were used to develop the wind and wave conditions used in the model.

The overall system performance and behavior were validated for eight sets of field measurements that span a wide range of operating conditions. The simulated controller response accurately reproduced the measured blade pitch and power. The structural and blade loads, and spectra of platform motion agree well with the measured data.

According to Roddier et al. (2017), in the design of WindFloat 1, two existing numerical tools were combined by Principle Power: OrcaFlex and FAST, to create a state-of-the-art floating wind turbine design tool called OrcaFAST. This tool is available commercially under the name FASTLINK. It was found that the numerical tools correctly predict the responses of engineering significance with some calibration.

Fowler et al. (2017) presented a summary of the research and development effort of the University of Maine on VolturnUS. In 2016 UMaine carried out testing of a 1:52-scale model of the 100% design of the VolturnUS with a 6-MW topside as a final design validation to support the U.S. Department of Energy supported, full-scale Aqua Ventus demonstration project. A 6-MW scale model turbine was used in this test. Selected results from the test campaign and preliminary numerical comparisons were discussed as well as key lessons learned from the model test campaigns were presented.

Utsunomiya et al. (2017) presented numerical modeling and validation of the numerical analysis model, the full-scale 2 MW Sakiyama hybrid-spar model. An aerohydro-servo-mooring integrated dynamic analysis tool was developed in this study. The tool was developed based on a commercially available multibody-dynamics solver (MBS), MSC.Adams and NREL/FAST. The wave forces are evaluated by Morison's equation with relative velocity formulation. The validation of the numerical analysis model has been presented by comparing the simulation results with the field measurement for the 2 MW hybrid-spar model. The comparison has been made for the natural periods and the response during the rated power production test. Basically, both comparisons have shown good agreement between the measured values and the simulation, showing the reliability of the developed code and the numerical model.

Caille et al. (2017) compared the numerical simulation results of the SBM TLP with the model test results. For the numerical simulation, two strategies are implemented to model the aerodynamic contribution. The Simplified Coupled Simulations (SCS), performed with OrcaFlex, use the aerodynamic forces recorded during the model tests to be imposed at the tower top; the Fully

Coupled Simulations (FCS), run with DeepLines Wind, use the aerodynamic loading computed with from the measured wind. The good agreement between numerical simulation and measurements was confirmed.

Skaare (2017) reviewed the development of the Hywind concept with a focus on numerical analysis tools, model and full-scale experiments, and control systems. Several analysis tools have been developed and matured over several years and verified against model and full-scale experiments. One example of a comparison between simulations using the SIMA analysis tool and full-scale measurements on the Hywind Demo was presented.

Choisnet et al. (2018) presented load validation for the Floatgen project. A coupled aero-hydro analysis of the full system has been carried out using FAST-Orcaflex (OrcaFAST) for the design of the tower and transition piece, the update of the controller, and the turbine loads verification. Turbine components include sensors that enable comparison of measurements to coupled calculations.

Bach-Gansmo et al. (2020) performed an investigation of the taut mooring system for the TetraSpar concept, both experimental and numerically. A 1:60 numerical model was modeled in the time domain simulation tool OpenFAST. The natural periods, free decay, and motions were compared. The experimental results indicate the nonlinear stiffness and second order wear loads are important effects for numerical modeling.

4.6.1.2 Tool Development and Validation

Modeling efforts for the development of integrated analysis tools are mainly on the following aspects:

- Different methods on hydrodynamic loads modeling
- Wind model and effects on aerodynamic loads
- Control system modeling
- Turbine blades and tower flexibility
- Hull structural flexibility
- Dynamic mooring line model
- Fiber rope stiffness model

Robertson et al. (2013) summarized the work done by the DeepCwind consortium members in analyzing the data obtained from the test campaign and its use for validating the offshore wind modeling tool, FAST. The DeepCwind consortium conducted a model test campaign in 2011 of three generic floating wind systems: a tension-leg platform (TLP), a spar-buoy (spar), and a semi-submersible (semi). Each of the three platforms was designed to support a $1/50^{th}$-scale model of a 5-MW wind turbine and was tested under a variety of wind/wave conditions.

Based on the validation work from the DeepCwind tests, the limitations of FAST have been identified as important areas for improvement to successfully model a floating offshore wind system.

These limitations include viscous drag, mooring model, second-order hydrodynamics, wave models, and higher fidelity structural and aerodynamic modeling.

Prowell et al. (2013) described the observed behavior of a tension-leg support platform (TLP), one of three platforms tested in the DeepCwind consortium, and the systematic effort to predict the measured response with the FAST simulation tool using a model primarily based on consensus geometric and mass properties of the test specimen. The results presented confirm that FAST produces meaningful results for the simulation of a TLP when a model is carefully calibrated. It is possible that the inclusion of second-order hydrodynamics and a dynamic mooring line model will contribute to improving simulation accuracy.

Gueydon et al. (2015) compared two FOWT simulation packages; (DIFFRAC+aNySIM) and (WAMIT+FAST) using a TLP platform supporting a wind turbine. The (DIFFRAC+aNySIM) package is developed by the Maritime Research Institute Netherlands. Then the effects of the second order loads on the response of a tension-leg platform (TLP) floating wind turbine were studied. The flexibility of the tower must be considered for this investigation; therefore, only FAST is used. The results of both packages in long-crested head waves are very close to each other. These simulations demonstrate that the flexibility of the tower of the turbine can have a major effect on the pitch motion of the TLP.

Second-order, high-frequency wave loads can trigger a resonance response of the pitch/tower first bending mode of the TLP. This resonance behavior can be reproduced by numerical tools based on potential flow if they include the second-order sum-frequency wave excitation. However, it should also be kept in mind that first-order wave loads can also trigger a resonance response of the pitch/tower first bending mode when this eigenfrequency is not high enough. In such a case, the effects of first-order wave loads would most likely mask those of the second-order sum-frequency loads, which are smaller by nature.

Wendt et al. (2015) presented the changes to the hydrodynamic load calculation algorithms in FAST v8, which are embedded in the HydroDyn module. HydroDyn is now capable of applying strip-theory (via an extension of Morison's equation) at the member level for user-defined geometries. Users may now use a strip-theory-only approach for applying the hydrodynamic loads, as well as the previous potential-flow (radiation/diffraction) approach and a hybrid combination of both methods (radiation/diffraction and the drag component of Morison's equation). Second-order hydrodynamic implementations in both the wave kinematics used by the strip-theory solution and the wave-excitation loads in the potential-flow solution were also added to HydroDyn. The new floating capabilities were verified through a direct code-to-code comparison.

Fleming et al. (2016) summarized the control design work that was performed to optimize the controller of a wind turbine on the WindFloat structure. A controller developed for a bottom-fixed wind turbine configuration was modified for use when the turbine is mounted on the WindFloat platform. This results in an efficient platform heel resonance mitigation scheme. The approach was tested in a fully coupled nonlinear aero-hydro-elastic simulation tool in which wind and wave disturbances were modeled. This testing yielded significant improvements in platform global performance and tower-base-bending loading.

FAST has been coupled to the OrcaFlex software package (called OrcaFAST) to simulate the coupled wind turbine and platform system. OrcaFlex is a time-domain simulation tool developed by Orcina that performs hydrodynamic analysis on offshore structures. The WindFloat platform and its mooring system were modeled in OrcaFlex. The turbine was simulated using FAST.

In the design of this floating controller, two important novelties were developed. First, both platform pitch and nacelle velocity were used simultaneously in control. Second, the controller was designed in the frequency domain both to separate the control activities of these loops and to trade off additional damping of resonant modes with the tendency of controllers to feedback wave frequency-range excitation.

Andersen et al. (2016) performed verification and validation of the multisegmented mooring capability of the FAST v8 modules: MAP++, MoorDyn, and the OrcaFlex interface. The OC3-Hywind spar buoy system tested by the DeepCwind consortium at the MARIN ocean basin, which includes a multisegmented bridle layout of the mooring system, was used for the verification and validation activities. All the listed modules are able to represent the platform motion observed in the experimental data to a satisfactory degree. MoorDyn and the benchmark tool (OrcaFlex) yield almost indistinguishable results.

Wendt et al. (2016) summarized the work performed to verify and validate two mooring dynamics modules: MoorDyn and FEAMooring. Results were compared to other mooring models and measured test data to assess their reliability and accuracy. The quality of the fairlead load predictions by the open-source mooring modules MoorDyn and FEAMooring appears to be largely equivalent to that predicted by the commercial tool OrcaFlex. Both mooring dynamic model predictions agree well with the experimental data, considering the given limitations in the accuracy of the platform hydrodynamic load calculation and the quality of the measurement data.

Robertson et al. (2017) summarized the findings from the Phase II of the Offshore Code Comparison Collaboration, Continued, with Correlation (OC5) project. The project is run under the International Energy Agency Wind Research Task 30 and is focused on validating the tools used for modeling offshore wind systems through the comparison of simulated responses of select system designs to physical test data.

The Offshore Code Comparison Collaboration (OC3) and Offshore Code Comparison Collaboration Continuation (OC4), operated under International Energy Agency Wind Tasks 23 and 30, were established to verify the accuracy of offshore wind turbine modeling tools through code-to-code comparisons. These projects were successful in showing the influence of different modeling approaches on the simulated response of offshore wind systems. Code-to-code comparisons, though, can only identify differences. They do not determine which solution is the most accurate. To address this limitation, an extension of Task 30 was initiated: The Offshore Code Comparison Collaboration, Continued, with Correlation (OC5). This project's objective is to validate offshore wind modeling tools through the comparison of simulated responses to physical response data from actual measurements. The project involves three phases using data from both floating and fixed-bottom systems, and from both scaled tank testing and full-scale, open-ocean testing.

In Phase I of the OC5 project, two different data sets were analyzed, both focusing on the validation of hydrodynamic loads on fixed rigid and flexible cylinders, with no wind turbine present. Findings from Phase I included the need for the proper choice of hydrodynamic coefficients, higher-order wave theory, complex seabed models, and nonlinear hydrodynamic theory (such as wave stretching and second- and higher-order models) to accurately predict the hydrodynamic loads and response of a structure.

For Phase II of the project, numerical models of the DeepCwind floating semi-submersible wind system were validated using measurement data from a 1/50th-scale validation campaign performed at the Maritime Research Institute Netherlands offshore wave basin. Validation of the models was performed by comparing the calculated ultimate and fatigue loads for eight different wave-only and combined wind/wave test cases against the measured data. A list of the tools used in this study is provided in the paper, which also shows the participant using the tool, and the modeling approach employed.

The results show a reasonable estimation of both the ultimate and fatigue loads for the simulated results, but with a fairly consistent underestimation in the tower and upwind mooring line loads that can be attributed to an underestimation of wave excitation forces outside the linear wave-excitation region, and the presence of broadband frequency excitation in the experimental measurements from wind. Participant results showed varied agreement with the experimental measurements based on the modeling approach used. Modeling attributes that enabled better agreement included: the use of a dynamic mooring model; wave stretching, or some other hydrodynamic modeling approach that excites frequencies outside the linear wave region; nonlinear wave kinematics models; and unsteady aerodynamics models. Also, it was observed that a Morison-only hydrodynamic modeling approach could create excessive pitch excitation and resulting tower loads in some frequency bands.

Ma et al. (2017) investigated the typhoon effect on the aerodynamic performance of the 5MW OC3-Hywind FOWT system, based on the Aero-Hydro-Servo-Elastic FAST code. First, considering the full field observation data of typhoon "Damrey" is a long duration process with significant turbulence and high wind speed, so one 3-hour representative truncated typhoon wind speed time history has been selected with the variable-speed and collective- pitch control strategy in operational mode. Second, the effects of both the (variable-speed and collective-pitch) control system of NREL 5 MW wind turbine and the motion of the floating platform on the blade aerodynamic performance of the FOWT system during the representative typhoon time history has been investigated. Finally, the effects of different wind turbine control strategies, control parameter combinations, wave heights, and parked modes on the rotor aerodynamic responses of the FOWT system have been clarified. The extreme typhoon event can result in considerably large extreme responses of the rotor thrust and the generated power. Further studies on the optimization of the control system to reduce loads may be required, especially for extreme typhoon events. One active-parked strategy has been proposed for reducing the maximum aerodynamic responses of the FOWT system during extreme typhoon events.

Pegalajar-Jurado et al. (2017) assessed the impact of different wave kinematics models on the dynamic response of a tension-leg-platform wind turbine. Aero-hydro-elastic simulations of the floating wind turbine are carried out employing linear, second order, and fully nonlinear kinematics using the Morison equation for the hydrodynamic forcing. The wave kinematics are computed from either theoretical or measured signals of free-surface elevation. The numerical results from each model are compared to results from wave basin tests on a scaled prototype.

The use of second order and fully nonlinear wave kinematics introduces sub-harmonic forcing, which in some cases, brings the numeric response closer to the test benchmark. In the superharmonic region, when there is linear wave energy, all models are able to show response at the coupled pitch-tower natural frequency. When such linear wave energy is not present, second order and fully nonlinear wave kinematics also introduce energy at the pitch-tower frequency. The response at the wave frequency range is better reproduced when kinematics are generated from the measured surface elevation. In the future, the numerical response may be further improved by replacing the global, constant damping coefficients in the model by a more detailed, customizable definition of the user-defined numerical damping.

Wendt et al. (2017) discussed several model calibration studies that were conducted for the DeepCwind semi-submersible in the OC5 project to identify model adjustments that improve the agreement between the numerical simulations and the experimental test data. These calibration studies cover wind-field–specific parameters (coherence, turbulence), hydrodynamic and aerodynamic modeling approaches, as well as rotor model (blade-pitch and blade-mass imbalances) and tower model (structural tower damping coefficient) adjustments. These calibration studies were conducted based on relatively simple calibration load cases (wave only/wind only). The agreement between the final FAST model and experimental measurements is then assessed based on more complex combined wind and wave validation cases.

Worsnop et al. (2017) examined a hurricane's turbulent eyewall using large-eddy simulations. Gusts and mean wind speeds near the eyewall of a category 5 hurricane exceed the current Class I turbine design threshold of 50 m/s mean wind speed and 70 m/s gust speed. The largest gust factors occur at the eye-eyewall interface. Further, shifts in wind direction suggest that turbines must rotate or yaw faster than current practice. Offshore wind energy development is underway in the U.S., with proposed sites located in hurricane-prone regions. Turbine design criteria outlined by the International Electrotechnical Commission do not encompass the extreme wind speeds and directional shifts of hurricanes stronger than category 2. Although current design standards omit mention of wind direction change across the rotor layer, large values (15–50°) suggest that veer should be considered.

Li et al. (2018) investigated wind field effects on the power generation and the aerodynamic performance of offshore floating wind turbines. For this purpose, three comparative wind fields are generated: a uniform wind field, a steady wind field with wind shear, and a turbulent wind field. Aero-hydro-servo coupled analysis is performed in a time-domain to estimate how a referenced semi-submersible offshore floating wind turbine behaves in the three wind fields.

The results reveal the importance of wind shear and inflow turbulence to the performance of the floating wind turbine. Thrust force and power generation become very unstable in the presence of inflow turbulence. Due to the control strategy of the wind turbine, the power generation is also correlated with the operational state and turbulence frequency. Although wind shear has a tiny effect on the rotor performance, the local aerodynamic load applied at a single blade experiences fluctuation with the presence of wind shear. It is also shown that the ultimate structural and fatigue damage loads at blade root are augmented by inflow turbulence and wind shear.

Doubrawa et al. (2019) addressed the lack of measurements of wind data by using high-fidelity, high-resolution simulation data as a reference. The international guidelines for wind turbine design specify two turbulence models to be used for simulating atmospheric conditions for load calculations: the Mann uniform shear turbulence model, and the Kaimal Spectrum Exponential Coherence (KSEC) model. Mainly due to the lack of physics, the flow fields simulated with these models ultimately differ in their underlying structure, especially in terms of the spatial coherence of longitudinal velocity perturbations. While this may not be critical for smaller wind turbine rotors, it becomes important when rotor sizes increase. Furthermore, it might be especially important in the context of floating technologies as they are more sensitive to large turbulent coherent structures.

While innovations in instrumentation (e.g., unmanned aerial vehicles and wind lidars) are ongoing, turbulence estimates from novel measurement techniques are still in the experimentation phase. As a result, previous studies seeking to understand the limitations of the IEC turbulence models either base themselves solely on lidar measurements (an approach that has not yet been validated against conventional sonic anemometry for coherence estimation) or use flow fields obtained with large-eddy simulations (LES) as a reference. Due to the limitations in available observation data sets, it was not able to obtain field measurements to support the research. Therefore, the latter approach was employed based on a validated LES code [the NREL Simulator fOr Wind Farm Applications (SOWFA] to generate the high-resolution reference turbulence fields against which Mann and KSEC are compared.

Hour-long, large-eddy simulations of turbulent velocity fields that are stability-dependent and contain three-dimensional coherent structures were performed. These flow fields are then used to investigate which stochastic model is a better predictor of loads on a realistic spar-system FOWT, and to quantify how the assumption of neutral stratification propagates to short-term load estimates. Both stochastic turbulence models are found to overpredict fatigue loading in high-wind scenarios (in some cases, by more than 25%) and underpredict it when the wind speed is low (by as much as 20%). The KSEC mode matches the high-fidelity flow fields more closely than Mann at high wind speeds, and the opposite is true at low wind speeds. Finally, turbine loading is found to be sensitive to atmospheric stability even when the turbulence intensity remains fairly constant. This sensitivity is most pronounced at low wind speeds when fatigue load estimates on the spar system can differ by 40%.

Johnson et al. (2019) focused on the verification of this new linearization functionality in OpenFAST, which is carried out by comparing results to previous stable versions of FAST. OpenFAST (formerly known as FAST), developed by the NREL, is a coupled aero-hydro-servo-elastic analysis tool for modeling FOWTs. A nonlinear time-domain simulation for a floating offshore platform is also compared to the time-domain response of the linearized state-space model. The linearized results show good alignment between OpenFAST and previous versions of FAST, as well as with the time-domain simulations, thereby showing the accuracy of the new features in OpenFAST.

Jonkman et al. (2019) presented the development plan of new capabilities in OpenFAST to model floating substructure flexibility and member-level loads, including the functional requirements and modeling approaches needed to understand and apply them correctly.

OpenFAST is an open-source, physics-based engineering tool applicable to the load analysis of land-based and offshore wind turbines, including FOWTs. The substructure for a floating wind turbine has historically been modeled in OpenFAST as a rigid body with hydrodynamic loads lumped at a point, which enabled the tool to predict the global response of the floating substructure but not the structural loads within its individual members. To enable the design and optimization of the floating substructures, especially next-generation floating wind technologies that show promise to be streamlined, flexible, and cost-effective, substructure flexibility and member-level load calculations are being implemented in OpenFAST. This implementation is part of a larger effort at NREL to develop an open-source, multi-fidelity systems-analysis capability for FOWT analysis and optimization that captures the relevant physics and costs that drive designs and trade-offs.

Robertson et al. (2019) presented a work to assess input parameters that have the greatest influence on turbine power, fatigue loads, and ultimate loads during normal turbine operation. An elementary effects sensitivity analysis is performed to identify the most sensitive parameters. Separate case studies are performed on (1) wind-inflow conditions and (2) turbine structural and aerodynamic properties, both cases using the NREL 5 MW baseline wind turbine. The Veers model was used to generate synthetic International Electrotechnical Commission (IEC) Kaimal turbulence spectrum inflow. The focus is on individual parameter sensitivity, though interactions between parameters are considered.

The results of this work show that for wind-inflow conditions, turbulence in the primary wind direction and shear are the most sensitive parameters for turbine loads, which is expected. Secondary parameters of importance are identified as veer, u-direction integral length, and u components of the IEC coherence model, as well as the exponent. For the turbine properties, the most sensitive parameters are yaw misalignment and outboard lift coefficient distribution; secondary parameters of importance are inboard lift distribution, blade-twist distribution, and blade mass imbalance. This information can be used to help establish uncertainty bars around the predictions of engineering models during validation efforts and provide insight into probabilistic design methods and site suitability analyses.

Tom et al. (2019) reviewed the process used to choose the bichromatic wave pairs to be applied in the campaign for the Offshore Code Comparison Collaboration, Continuation, with Correlation and unCertainity (OC6) project to validate the second-order difference-frequency quadratic and potential loads at the surge and pitch natural frequencies of a floating semi-submersible. Through this work, a set of bichromatic wave cases were defined for investigating the second-order hydrodynamic loading on the OC5-DeepCwind semi-submersible.

The focus of the OC6 project, which operates under the International Energy Agency Wind Task 30, is to refine the accuracy of engineering tools used to design offshore wind turbines. In support of this work, a new validation campaign is being developed that seeks to better understand the nonlinear wave loading that excites floating wind systems at their low-frequency, rigid-body modes in surge and pitch. The validation data will be employed in a three-way validation between simplified engineering tools and higher-fidelity tools, such as CFDs. Irregular wave spectrums, which are traditionally used to examine the nonlinear wave interaction with offshore structures, are too computationally expensive to be simulated in CFD tools, and so we will employ bichromatic wave cases instead.

Robertson et al. (2020) discussed experimental uncertainty for FOWT model tests. Quantifying the uncertainty in experimental results is a critical step in properly validating numerical simulation tools for designing floating wind turbines; without a good understanding of the experimental uncertainties, it is impossible to determine if numerical simulation tools can capture the physics with acceptable accuracy. Previously assessed systematic uncertainty components in hydrodynamic tests of the OC5-DeepCwind semi-submersible are propagated to response metrics of interest using numerical simulation tools and combined with the system's random uncertainty to obtain the total experimental uncertainty.

Considering response metrics that give an indication of the wave-frequency and low-frequency responses of the system, the wave frequency responses are found to have relatively small uncertainty, while the uncertainty in the low-frequency responses is somewhat higher. The main contributions to the propagated systematic uncertainty in low-frequency responses were primarily model characteristics that affected the stiffness: mooring system stiffness for the surge response, and platform draft, and vertical center of gravity for the pitch response. In addition, uncertainty in the wave amplitude also had an impact. The simulation tools applied in the study showed good agreement regarding which parameters were most important, although the magnitude of the propagated uncertainty differed significantly among participants.

A major limitation in the present work is the use of simulation tools for uncertainty propagation. The inconsistent estimation of the baseline value of the low-frequency power spectrum sums suggests that the modeling tools may not be sufficiently accurate to be used for uncertainty propagation. At present, however, these tools represent the state-of-the-art, and the results of the present study suggest that the differences between experiments and simulations are larger than the uncertainty in the experimental results.

Moan et al. (2020) performed a review of recent advances in integrated response analysis of FOWTs from a reliability perspective. The main challenges, especially for novel floating wind turbine concepts, are to increase reliability and reduce costs. The reliability perspective here refers to the lifecycle integrity management of the system to ensure reliability by actions during design, fabrication, installation, operation, and decommissioning.

Recent developments of methods for numerical and experimental response assessment of floating wind turbines are briefly described in view of their use to demonstrate system integrity in design as well as during operation to aid inspection and monitoring. Typical features of offshore wind turbine behavior are also illustrated through some numerical case studies.

Information about the blades, tower, and support structures are readily available for realistic research studies, especially for the widely studied reference turbines such as the NREL 5 MW and DTU 10 MW turbines. However, less information about drivetrains or commercial control systems is in the public domain. While the reference turbines include simplified control system definitions, the lack of publicly available information regarding details of the blade pitch and generator torque control, in particular for floating wind turbines, results in challenges for comparisons against full-scale measurements (of which few are available) and for detailed study of wind turbine subcomponents.

The design takes place in stages, from conceptual to detailed design, requiring different degrees of refinement. A variety of methods, refined and simplified, is hence desirable for dealing with the aerodynamics, hydrodynamics, structural, and possible soil mechanics. In general, simplified, efficient methods are required to accomplish analysis in the early design stages when alternative designs need to be assessed to achieve an optimal design.

The need for carrying out an integrated dynamic analysis as a basis for design is highlighted, based on a hydro-, aero-, servo-elastic model with proper representation of the sub-systems: rotor, drivetrain, hull, mooring, and power cable and in such a way that the load effects in the sub-systems can be determined for use in their integrity assessment. At the same time, efficient simplified models are needed, and higher fidelity models for components such as the drivetrain or pitch actuator system may be required.

4.6.2 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD), as a high-fidelity modeling method, is now applied in several areas in FOWTs:

- Nonlinear hydrodynamic loads, slamming, impact loads
- Aerodynamic loads
- Wake effects

CFD analysis is considered to have high accuracy levels. However, the main disadvantage of CFD is time consuming.

Benitz et al. (2014) compared hydrodynamic loads for the OC4-DeepCwind semi-submersible using FAST that employs Morison's equation and potential-flow theory and the high-fidelity CFD package, OpenFOAM.

A fixed semi-submersible was simulated in current-only and waves-only conditions to assess differences in load predictions in the two codes. For the current-only conditions, a comparison of load predictions from the two codes showed larger drag forces from FAST than from OpenFOAM. This may be the result of the natural simulation of shadowing effects in OpenFOAM, where downstream members are shielded by upstream members, or from differences in the drag coefficient. Results from FAST do not account for lift forces, which can be captured by CFD analysis. For wave-only conditions, in these cases, the inline-force predictions from FAST and OpenFOAM were in excellent agreement, but again, the FAST results did not capture any lift forces.

Dunbar et al. (2015) developed an open-source CFD/6-DOF (Degree-Of-Freedom) solver using OpenFOAM for high-fidelity simulation of FOWT platforms. Validation of the tightly coupled CFD/6-DOFsolver is carried out on a benchmark case of the free decay of a heaving cylinder. The solver is then used in simulations of the DeepCwind semi-submersible platform and compared with FAST. Free heave and pitch decay were simulated. Overall, the results demonstrate that the tightly coupled solver compares well with FAST. The tightly coupled CFD/6-DOF solver represents an advance in the modeling of offshore wind turbine platform dynamics using open-source software that may be used for wind turbine research, design, and analysis.

Beyer et al. (2015) numerical calculations of the IDEOL Floatgen floating foundation with regular waves using coupled Multibody System (MBS)-CFD methods are compared to experimental data of the 1:32 scale mode test. Results of the wave elevation, floater motion, and mooring line tension show a very good correlation. Flow phenomena like vortex shedding at the hull of the floater are shown. The presented methodology provides detailed knowledge allowing analysis of wave impact and resulting load assessment of floating offshore structures.

The floating foundation experiences a complex flow phenomenon. The IDEOL FOWT foundation has strong heave damping due to the entrapped water in the damping pool. While the floater is moving, water flows in and out of the pool, similar to a piston in an engine resulting in induced viscous drag. Wave sloshing can be observed in the pool. Also, the water level in the pool is different compared to the wave elevation in front of the floating foundation. The shed vortices around the floating foundation are strongly three-dimensional. This flow phenomenon can only be captured by high fidelity CFD simulations.

Borisade et al. (2016) performed design studies of the IDEOL mooring foundation at the hull and to investigate the full-scale floater concept in a coupled MBS-CFD environment at regular waves. First, the mooring foundation is simulated with increasing complexity, and results are compared for global floater motion and flow characteristics. Second, the floater is simulated at full scale and compared to the upscaled results of the model scale-up.

Floater motion in a surge, heave and pitch, and relative wave elevation sensors show a very good correlation between numerical and experimental results. Increasing the complexity of the mooring foundation results in a higher pitch response. Air is entrapped in a chamber in the full mooring foundation and is decompressed during a wave period. The full-scale simulation shows a good accordance to model scale results, indicating good agreement with Froude similitude. The presented methodology provides very satisfactory results for load assessment and design optimization of various types of offshore structures.

Liu et al. (2017) described a numerical tool based on the open-source CFD toolbox OpenFOAM for application to FOWTs. Various benchmark cases are first modeled to demonstrate the capability of the tool. The OC4 DeepCWind semi-submersible FOWT model is then investigated under different operating conditions.

The engineering tool FAST uses an input of a hydrodynamic database computed by an external potential-flow solver (such as WAMIT) to predict hydrodynamic loading. In terms of wind turbine aerodynamic loading, FAST adopts a conventional Blade Element Momentum (BEM) method with various empirical and semi-empirical correction models. As the wind flow conditions are rather complex for a FOWT, considering the dynamic interaction between the wind turbine and its wake due to the platform motions, the BEM method may not be well valid. Apart from the BEM methods, vortex methods are also used to model wind turbine aerodynamics. With the use of lifting lines or surfaces to represent rotor blades, trailing, and shed wake in vortex methods, one is able to describe the 3D flow around a wind turbine and to have a better insight into the flow development than with the use of the BEM methods.

In contrast to the aforementioned methods, as CFD methods inherently take fluid viscosity into account, the hydrodynamic drag forces acting on a floating platform can be directly calculated in both inline and transverse directions. Furthermore, CFD methods are able to model the dynamic interaction between fluid flow, wind turbine, and floating platform. With the use of a CFD tool, direct modeling of FOWT systems is possible, and full-scale simulations can be performed. Therefore, the scale effects will no longer be present in the predictions. With these advantages, there is an increasing trend to analyze FOWT systems using CFD tools.

The OC4 DeepCWind semi-submersible FOWT model was analyzed using the fully coupled fluid-structure interaction (FSI) analysis tool under combined wind-wave excitation. Three degrees of freedom responses of the floating structure, which are surge, heave, and pitch are taken into account here, while the other three modes of motion (sway, roll, and yaw) are ignored. Since a FOWT is a coupled system, the present numerical modeling and data analysis also extends the normally focused aspects to the influences of floating platform motions on the wind turbine aerodynamic performance and vice versa under various wind speed and wave conditions.

With this tool, the effects of the dynamic motions of the floating platform on the wind turbine aerodynamic performance and the impact of the wind turbine aerodynamics on the behavior of the floating platform and on the mooring system responses are examined. The present results provide quantitative information of three-dimensional FSI that may complement related experimental studies. In addition, CFD modeling enables the detailed quantitative analysis of the wind turbine flow field, the pressure distribution along with blades, and their effects on the wind turbine aerodynamics and the hydrodynamics of the floating structure, which is difficult to carry out experimentally.

Mucha et al. (2019) presented an investigation into the computation of hydrodynamic loads on a suspended cylinder in regular waves. The primary goal was to perform a three-way validation of the loads between experimental measurements and simulations from two computational methods. Experimental measurements of the longitudinal in-line force on a cylinder suspended at a fixed position were available from the Offshore Code Comparison Collaboration, Continued, with

Correlation (OC5) project, Phase Ia. These measurements were compared to CFD simulations based on the solution of Reynolds-averaged Navier-Stokes (RANS) equations, as implemented in STAR-CCM+. The analysis was supplemented by results generated with the offshore wind turbine engineering software OpenFAST, based on a hybrid combination of second-order potential flow and viscous drag from Morison's equation.

Time series of free surface elevation and in-line forces were compared to experimental measurements. The favorable agreement was observed for first-order load contributions across all methods and variations within these methods. Substantial differences were observed in the numerical prediction of the second and third harmonic force contribution.

4.6.3 New Methods Under Development

New methods under development are mainly in the following areas:

- Wake Effects
- Control co-design
- Structural flexibility and global loads

4.6.3.1 Wake Effects

According to Barter et al. (2020), to develop a successful commercial wind project, one needs to not only consider the design of the individual turbine systems but the design of the entire wind plant. Plant design focuses on the array placement (or layout) of the turbines and the control strategies that will maximize power and minimize loads across the plant. Land-based and fixed-bottom turbines have yaw motors to align with the dominant wind direction, and yaw-based steering of wakes away from downstream turbines is an active area of research. However, recent preliminary analysis has shown that wake-steering via tilting or pitching an upstream rotor has even greater potential for maximizing power production. Most of these studies to date have focused on land-based or fixed-bottom applications and will need to be revisited for the floating application with compliant motion. The degree of platform motion will likely require new aerodynamic tools before attacking plant-level flow control and array optimization. Future floating wake steering research will also have to consider the different degrees of yaw or tilt control authority on a floating platform.

Rodrigues et al. (2015) presented a novel layout optimization framework for wind farms composed of moveable floating turbines. The proposed framework uses an evolutionary optimization strategy in a nested configuration, which simultaneously optimizes the anchoring locations and the wind turbine position within the mooring lines for each individual wind direction. The results show that maximum energy production is obtained when moveable wind turbines are deployed in an optimized layout. In conclusion, the framework represents a new design optimization tool for future offshore wind farms composed of moveable floating turbines.

To reduce costs (e.g., cabling and area rental costs), turbines tend to be packed in wind farms. However, installing turbines close to each other causes interferences such as wake losses through shadowing. For example, the efficiency of the Danish Horns Rev I offshore wind farm is 89% of what the same turbines would produce if installed alone. Thus, it is important to reduce the wake losses in far and large offshore wind farms. One possible strategy to reduce wake losses is to optimize the wind farm layout.

Currently, there is a wide variety of models to calculate, with different accuracy levels, the wake losses inside wind farms. Examples of wake losses models to calculate the wind deficits due to wakes inside wind farms include the Jensen model (also known as Park model), Eddy viscosity model, Frandsen et al. model, deep-array wake model, and the Larsen model. These engineering models, due to their simplified wake speed deficit approach, offer fast calculation times, and are able to provide a preliminary description of the far wake regime (4–6 rotor diameters). Other models were built to provide medium-fidelity results, namely the Dynamic Wake Meandering model and several other approaches based on the actuator disk model. CFD models stand in the high-fidelity end. Examples of CFD models are the Simulator for Offshore Wind Farm Applications (SOWFA), a modular and open-source tool developed by NREL, the EllipSys3D developed by DTU and Risø, and FarmFlow developed by the Energy Research Centre of the Netherlands (ECN). Finally, high-resolution models based on large eddy simulations (LES models) offer the highest fidelity but may take several weeks to complete.

Two models are used in this work to calculate the wake losses inside an offshore wind farm. The Jensen model is employed during the optimization routine, whereas FarmFlow is used to verify the efficiency of the optimized wind farm layouts. The Jensen model is a simplified and fast manner of calculating the wind speed inside the wake of a wind turbine. This model, due to this ease of implementation and fast computation, has been widely adopted in wind farm modeling. FarmFlow model solves the parabolized Navier–Stokes equations in all three dimensions.

The results obtained in this work corroborate that turbine and wind farm developers should cooperate to optimize future offshore wind projects. As future work, the optimization framework can be extended to assess the energy gain for different wind farm sizes and different turbines.

Wise and Bachynski (2019) simulated two 10 MW semi-submersible FOWTs, separated by eight rotor diameters (D) in the wind direction, with an ambient wind speed of 10 m/s and in moderate wave conditions using FAST. Farm to investigate the effects of wakes on global responses. Synthetic inflow is generated using three methods: the Kaimal turbulence model, 1) without and 2) with spatial coherence in the lateral and vertical velocity components, and 3) the Mann turbulence model (where spatial coherence in all three dimensions is inherent to the model).

FAST.Farm is a new wind farm Multiphysics modeling tool that has been developed by the NREL. Instances of OpenFAST (the latest version of FAST) within FAST.Farm model the nonlinear, dynamic behavior of distinct turbines. Especially important to FOWT, FAST.Farm includes wind turbine motion when updating the wake deficit and center line. While FAST.Farm was originally developed to compute the ambient wind farm-wide using a precursor large-eddy simulation. Recent updates allow the inflow to be generated more easily using a synthetic turbulent wind model.

The first method results in negligible wake meandering, a relatively uniform wake deficit, while the second and third methods result in the meandering of the upstream turbine's lateral wake center at the downstream turbine's rotor plane of up to approximately 1D and 1.5D, respectively. The slow meandering behavior of the upstream turbine's wake resulted in increased low-frequency platform motions for the downstream turbine. Yaw motions were especially susceptible to wake meandering as the standard deviation of the downstream turbine's yaw motion increased by 28.0 % for the second method and 11.3 % for the third method. Increased low-frequency response in structural loading was also observed. Wake effects led to between 2 % and 30 % greater fatigue damage at the top of the tower for all three methods and at the base of the tower for the second method. However, other results were found to be sensitive to the blade-passing frequency.

Johlas et al. (2019) used large eddy simulations with an actuator line model to study downstream wake characteristics of the NREL 5 MW reference turbine mounted on the OC3-Umaine spar platform for several different metocean conditions.

Wind turbine wake effects can decrease power output and increase turbine loads, especially for turbines in wind farm arrays. A better understanding of wake physics allows for improved engineering wake models used in the design. Wakes of FOWTs are difficult to accurately model, due in part to the coupled nature of FOWT rotor aerodynamics and platform motion. To meet this challenge, large eddy simulations (LES) coupled with reasonable platform motions are increasingly used to study FOWT rotor aerodynamics and wakes.

For the simulated conditions, wakes of FOWT have similar characteristics to fixed-platform wakes. Small differences in wake shape are associated with mean platform displacements, particularly a 5-10% upward deflection of the wake due to mean platform pitch. In contrast, variations in turbulence are associated with time-varying platform motions, particularly a 1-6% increase in peak turbulent kinetic energy (TKE) in the wake shear layer. These differences persist into the far wake 6 to 9D downstream but are reduced for higher wind speeds or lower wave heights. Rotor yaw angle and wind-wave alignment only minimally affect the differences between fixed- and floating-platform wakes. Due to mesh resolution limitations, these results may not capture all floating-platform wake effects. Future work will address if these small but non-negligible wake differences produce significant effects on the power output or mechanical loads of a downstream turbine.

Wise and Bachynski (2020) used FAST.Farm to simulate a two-turbine case with three different FOWT concepts: a semi-submersible (semi), a spar, and a tension leg platform (TLP), separated by eight rotor diameters in the wind direction. Synthetic inflow is generated using both the Kaimal turbulence model and the Mann turbulence model.

FAST.Farm was originally developed to compute the ambient wind farm wide using a precursor high-fidelity large-eddy simulation (LES); recent updates allow the inflow to be generated using synthetic turbulent wind models. There has been success modeling wake dynamics using less computationally expensive mid-fidelity methods where a dynamic wake meandering (DWM) model is coupled with an aeroelastic simulation tool. In a DWM model, the wake flow field is treated using a splitting of scales methodology where turbulent eddies greater than two diameters affect wake meandering, and those smaller than two diameters affect the wake-deficit evolution. This model has been implemented in FAST.Farm as well.

Since wake meandering varies depending on the environmental conditions, three different wind speeds (for all three concepts), as well as two different turbulence levels (for the semi), are considered. For the below-rated wind speed, when wake meandering was most extreme, yaw motion standard deviations for the downstream semi were approximately 40% greater in high turbulence and over 100% greater in low turbulence when compared with the upstream semi. The low yaw natural frequency (0.01Hz) of the semi was excited by meandering, while quasi-static responses resulted in approximately 20% increases in yaw motion standard deviations for the spar and TLP. Differences in fatigue loading between the upstream and downstream turbines for the mooring line tension and tower base fore-aft bending moment mostly depended on the velocity deficit and were not directly affected by meandering. However, wake meandering did affect fatigue loading related to the tower top yaw moment and the blade root out-of-plane moment.

Kopperstad et al. (2020) studied the wake dynamics behind a compliant FOWT with two alternative supporting platforms of spar buoy and barge platform numerically. The computational model is based on the large eddy simulation and the use of the actuator disk model of the rotor in which the circular actuator disk is discretized with an unstructured two-dimensional triangular mesh in a structured three-dimensional Cartesian grid of the fluid domain.

In this work, the only one-way coupling between the wave-induced motion of the platform and aerodynamics of the wake is considered. The wake dynamics and platform motions are calculated for laminar and turbulent inflow conditions. The flow solver is verified through a series of experimental wake measurements done behind a porous disk model and is also cross validated against previously published results. The dynamics of the floating spar and barge structures are calculated for three distinctive sea states. The time history of power extraction and wind force for the FOWT are recorded and compared against a fixed horizontal axis wind turbine. The motion of the barge platform is found to induce low-frequency modulation of the wake, whereas the spar buoy primarily displays similar wake dynamics to the fixed turbine. It is discussed how a single turbine utilizing the spar concept can be more energy-efficient under the wave-induced motion. Moreover, for both laminar and turbulent inflow conditions, due to the large axial oscillation experienced by the barge concept, the turbine wake recovers more rapidly. This suggests that for a tighter spacing of the turbines in a farm, the barge platform concept can be leveraged to obtain higher energy capturing efficiency over the same farm area.

It is planned to conduct future experimental studies on validating the observations made in this paper. Additionally, we are in the process of expanding this study into a wind farm configuration to investigate the aerodynamic interaction within a small floating farm and the possibility of using the dynamic interactions between turbines for maximum power efficiency. Another improvement of this study is related to the refinement of the rotor representation and the use of a more detailed computational model of the rotor blades.

4.6.3.2 Control-Co-Design Method (CCD)

According to Barter et al. (2020), generally, the state of the art technology for floating wind turbine systems is to design platforms that are inherently resistant to wind and wave excitation and modify the fixed-bottom wind turbine control system to reduce oscillations further. However, these adapted fixed-bottom offshore control strategies are most likely suboptimal in floating systems. The compliant nature of the floating wind system allows for large motion excursions, producing low-frequency oscillations in the translational (surge, sway, heave) and rotational (pitch, roll, yaw) degrees of freedom. These large motions lead to increased inertial loading in the system, which must be mitigated to keep the support structure at a reasonable size and to prevent excess fatigue loading on the turbine, which could shorten its life. Using a control strategy developed for fixed-bottom turbines in a floating application could induce significant instability. Different FOWT design concepts will exhibit different behaviors in each degree of freedom, and as such, have different requirements for their controllers. Control strategies that emphasize co-design, where the entire system and controller are designed together, will offer the greatest performance benefit. This may include new active and/or passive actuation technologies that increase damping to wind and wave excitations.

4.6.3.3 Floating Substructure Flexibility and Structural Global Loads

In the integrated analysis, the current state-of-art program normally considered the flexibility of the blades and the tower. However, the flexibility of the floating substructure is not considered. Structural global loads are normally only given at the tower bottom. For the floating substructure design, a separate procedure is normally applied to derive the structural global loads for structural design.

There are some developments, both experimentally and numerically (Hegseth et al., 2018; Luan et al., 2018; Jonkman et al., 2019; Engebretsen et al., 2020). These methods are still under development and currently are not streamlined for structural analysis for floating substructure design.

4.6.4 Technological Challenges

The technological challenges in numerical modeling are mainly in the following areas:

- Nonlinear hydrodynamic load modeling is critical for motion and global load analysis. Numerical modeling needs further improvement.
- Integrated analysis tools to include global structural loads and structural member flexibility for structural analysis are not available and not streamlined.
- Modeling tools for control co-design are still under development.

5 ENVIRONMENTAL ASSESSMENT

This environmental assessment provides a summary of assessments of environmental issues specifically associated with FOWTs on the Outer Continental Shelf (OCS) of California, Oregon, Hawaii, and Maine. Research and data were gathered from a variety of sources, including:

- Existing Floating Offshore Wind Projects, including three in the United Kingdom and the Hywind Tampen project in Norway.
- Environmental assessments (EA) completed on the wildlife impact of wind power in areas of interest
- Assessments of navigation impacts of FOWTs
- The experience the Aqua Ventus scaled FOWT in the Gulf of Maine
- The experience of the Vineyard Wind 1 Fixed Offshore Wind Farm project offshore Massachusetts

The research focused on environmental issues unique to FOWT, including:

- **Fishing**: Concerns over the impact that FOWT sites may have on the commercial fishing industry, particularly the likelihood that fishing will need to be excluded from FOWT sites and a surrounding radius
- **Shipping/Navigation**: Concerns that FOWT sites could interfere with navigation within established commercial shipping routes or present hazards to navigation from mooring systems or dynamic submarine cables.
- **Pelagic Life:** Concerns that marine mammals and fish could be adversely affected by FOWTs, with specific risks including:
    - The entanglement of marine mammals in mooring lines, inter-array cables, and export cables
    - Harm to marine mammals and fish from chemical spills from the FOWT
    - Harm to marine mammals and fish from excess noise
    - Displacement of marine mammals and fish from their habitats.

In addition, a FOWT has a similar or less environmental impact than a fixed offshore wind turbine in the following categories:

- Terrestrial and Coastal Fauna
- Coastal Habitats
- Benthic Resources
- Sea Turtles
- Birds and Bats
- Cultural Resources
- Historic Properties

- Marine and Terrestrial Archaeological Resources
- Recreation and Tourism
- Land Use and Coastal Infrastructure
- Environmental Change
- Visual Impact
- Underwater Noise

These issues and sub-issues will generally be looked at with particular emphasis on the stages of the FOWT lifecycle, as the issues can become exacerbated or naturally mitigated depending on the current stage of the FOWT. The lifecycle stages are:

- **Construction Phase:** The construction phase at sea of a FOWT consists primarily of towing the project out to sea, setting up the mooring lines, and laying the cables. Work vessels congregate around the site to complete construction. The construction phase at sea of a FOWT is much shorter and less invasive than that of a traditional Fixed-Bottom Offshore Wind Turbine, as fabrication and assembly of the FOWT are done on or near shore and pile driving is not involved. The EAs of the UK FOWTS (Kincardine, 2016; Statoil, 2015; Dounreay, 2016) project Construction phases lasting a matter of weeks.

- **Operation & Maintenance (O&M) Phase**: The O&M phase in the FOWT lifecycle is the long-term period during which the turbines are operating at full speed, and work vessels frequent the site for needed and routine maintenance. The EAs of the UK projects project O&M phases between 20 and 30 years.

- **Decommissioning Phase**: The decommissioning phase at sea of a FOWT consists primarily of removing the mooring lines and cables and towing the project back to shore. Work vessels congregate around the site in order to complete decommissioning. As with the construction phase, the decommissioning at sea of a FOWT is much shorter and less invasive than that of a traditional Fixed-Bottom Offshore Wind Turbine. The EAs of the UK FOWTS (Kincardine, 2016; Statoil, 2015; Dounreay, 2016) project Decommissioning phases lasting a matter of weeks.

ABSG's review of environmental assessments found that some issues relating to fishing, shipping, or pelagic life are more prominent in Construction and Decommissioning phases, while others are primarily issues during the O&M phase. Collision and allision risks, for instance, are more likely to occur during Construction and Decommissioning phases than in the O&M phase due to the congregation of work vessels, and as such may require greater mitigation focus during those phases than during O&M. The following sections detail the review of assessments regarding fishing, shipping/navigation, and pelagic life issues during the FOWT lifecycle, along with potential mitigation techniques recommended by those assessments.

5.1 FISHING IMPACTS

5.1.1 Overview

ABSG reviewed available fishing impact information from existing FOWT projects to determine how a FOWT site in the OCS would potentially impact U.S. fishing activities. The review included EAs from four existing European FOWT and published information on the Fukushima FORWARD project (Fukushima Offshore Wind Consortium, n.d.) in Japan. Three of the European projects, Kincardine (2015), Hywind Scotland (Statoil, 2015), and Dounreay (2016), are in the United Kingdom, while the fourth, Hywind Tampen, is in Norway (Equinor, 2019).

5.1.2 Review of Existing FOWTs -Construction & Decommissioning Phases

The Kincardine EA (Kincardine, 2016) found that fishing activities should be excluded from a 500-meter radius around the FOWT site during the Construction and Decommissioning phases due to safety hazards facing fishing vessels. In particular, the Kincardine EA found that fishing vessels during the Construction and Decommissioning phase faced a heightened risk of collision and allision with work vessels and the FOWT structure, respectively. Collision risk, in particular, was assessed to be high due to the higher than the typical density of work vessels in the vicinity during both the Construction and Decommissioning phases. Ultimately, Kincardine assessed the Construction and Decommissioning phases to be a serious risk to fishing activities, and that those fishing activities needed to be excluded from a 500-meter radius around where the project is being constructed.

The Hywind Scotland EA (Statoil, 2015) found similar results as the Kincardine assessment during the Construction and Decommissioning phases. Namely, collision and allision risks pose a significant danger to fishing vessels. The Hywind EA recommended fishing exclusion zones of 500 meters be implemented around the FOWTs for the duration of both the Construction and Decommissioning phases, and while the export cable is being laid. Due to the risks of collision between fishing vessels and work vessels laying the cables, a “safety zone” was also recommended by the Hywind EA of 500 meters around the vessels laying the cables.

The Dounreay EA (Dounreay, 2016) discussed the impacts on fishing during Construction / Decommissioning supported the findings of the Kincardine and Hywind Scotland assessments, noting that Construction and Decommissioning activities will crowd traffic lanes and create collision/allision hazards for passing vessels. As such, the Dounreay EA also recommends a 500-meter fishing exclusion zone around the FOWTs. As with the Hywind Scotland EA, the Dounreay EA recommended fishing vessels be excluded from the vicinity of the export cable while the cable is being laid.

Equinor’s Hywind Tampen (Equinor, 2019) was approved by the Norwegian government in 2020. The impact assessments for the project included fishing activities within and around the wind farm and yielded similar conclusions as the UK EAs. The impact assessments found that fishing using bottom trawl and purse seine gear would likely need to be excluded from the FOWT site and an area around the site during the Construction and Decommissioning phases as construction vessels install/remove suction anchors, mooring chains, and power cables. Fishing exclusions will apply around the towing operations to install the FOWTs.

5.1.3 Review of Existing FOWTs/Recent Research Efforts-O&M Phase

The Kincardine EA (Kincardine, 2016) recommends a fishing exclusion zone of 500 meters around the FOWT site during the O&M phase, finding that fishing activities, particularly those involving towing gear, cannot operate safely in the area of the turbines. The Kincardine EA found that while collision/allision risk is lower in the O&M phase than in the Construction or Decommissioning phases because of the lower volume of work vessels nearby, the risk is still present. The risk to fishing vessels includes:

- Risk of collision with service vessels
- Risk of fishing vessel losing power, drifting, and alliding with a FOWT
- Risk of FOWT mooring lines failing, resulting in the entire WTG drifting and causing a navigation hazard

The greater risk to fishing vessels during O&M, the Kincardine EA found, is gear being snagged on mooring lines or inter-array cables. Consequences of such accidents are likely to be severe due to the potential for serious property damage and personal injury (Kincardine, 2016)

The Hywind Scotland EA (Statoil, 2015) found, as the Kincardine assessment did, that the primary risks during the O&M phase of the FOWT lifecycle are mid-water mooring lines and inter-array cables posing a snagging risk. The Hywind Scotland EA recommended a fishing exclusion zone of 500 meters around the FOWT vicinity, judging snagging risks is sufficiently high that fishing activities cannot be conducted safely. During O&M, however, fishing vessels are expected to be able to operate in the export cable corridor, particularly if those cables are buried and made to be over-trawlable.

The Dounreay EA (Dounreay, 2016) supported the findings found in the Kincardine and Hywind Scotland assessments that mooring lines and inter-array cables pose a serious snagging risk to fishing gear. Fishing activity is recommended to be excluded from the immediate 500 meters around the FOWT site with no exclusion in the export cable corridor.

In summary, the UK FOWTs projects generally indicate similar findings:

- Serious collision/allision risk during the installation of FOWTs, moorings, and cables necessitates fishing exclusion zones, generally up to 500 meters throughout Construction and Decommissioning phases.

- Serious risks of fishing gear snagging on mooring lines and inter-array cables during the O&M phase, as well as the continued risk of collision/allision, means that fishing activities cannot be safely undertaken in the vicinity of the turbines. An exclusion zone, generally of up to 500 meters, was recommended.

- Fishing can occur in the vicinity of the export cables during O&M, and excluded during Construction or Decommissioning, when the cable is being laid or removed, respectively.
- Fishing excluded from the vicinity of FOWTs during the O&M phase, there will be a displacement effect on fishers that normally use prospective FOWT grounds. This displacement effect will, in turn, create pressure in other areas to which fishers are displaced.

The Hywind Tampen (Equinor, 2019) impact assessment recommended during the O&M phase, fishing in and around the FOWT site using bottom trawl, purse seine, and other bottom-dragging fishing gear to be excluded with a 500-meter safety zone around the site. The developer will design the anchors around the outside of the FOWT site to be over trawlable as they will be located beyond 500 meters from the FOWTs. The impact assessment also found that for float trawl fishing, only incidental activity has been recorded in and around the planned wind farm, but a risk to all trawl fishing exists due to the free hanging sections of the power cables and anchoring systems. Figure 58 shows the dynamic power cable from the FOWT anchored to the seabed at a depth of 260 to 300 meters with the cable floating free in between with buoyancy floats to relieve stress on the cable and provide enough slack as the FOWT moves. The cable is connected to the seabed about 400 to 500 meters from the FOWT. The impact assessment did not provide the depth of the floating section of the cable.

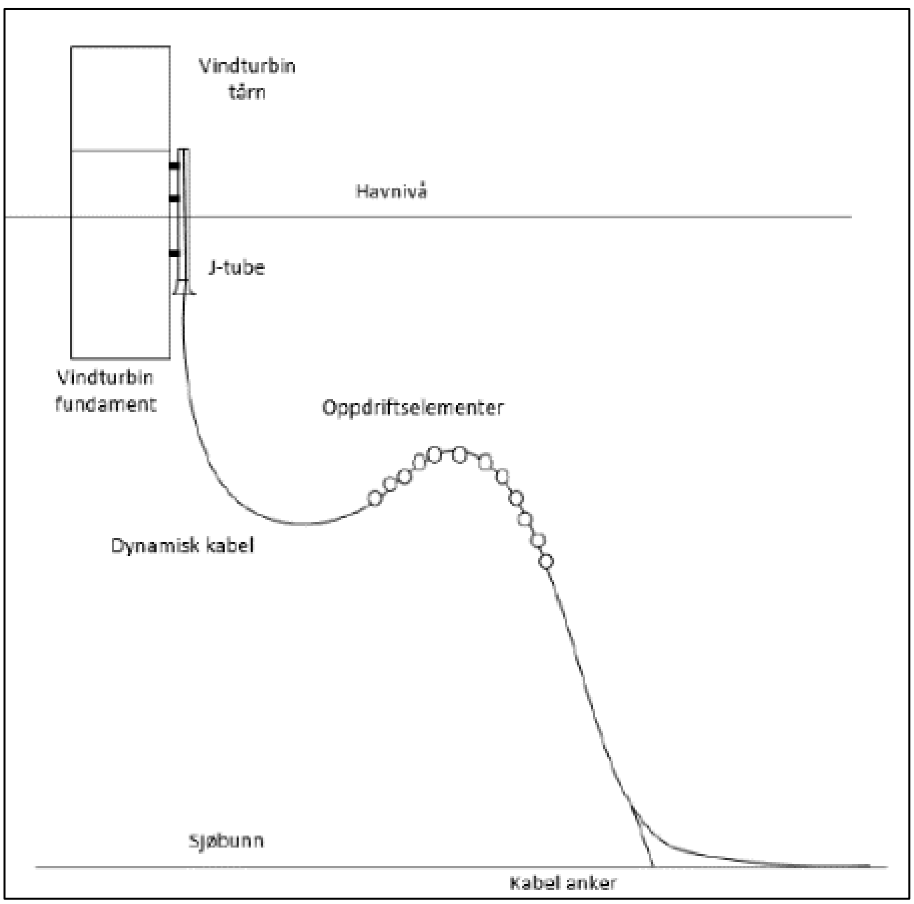


Figure 58 Hywind Tampen dynamic power cable in the water column (Equinor, 2019)

Each anchor chain extends approximately 800 meters from the turbine, with approximately 600 meters resting on the seabed under moderate wind conditions, as shown in Figure 59.

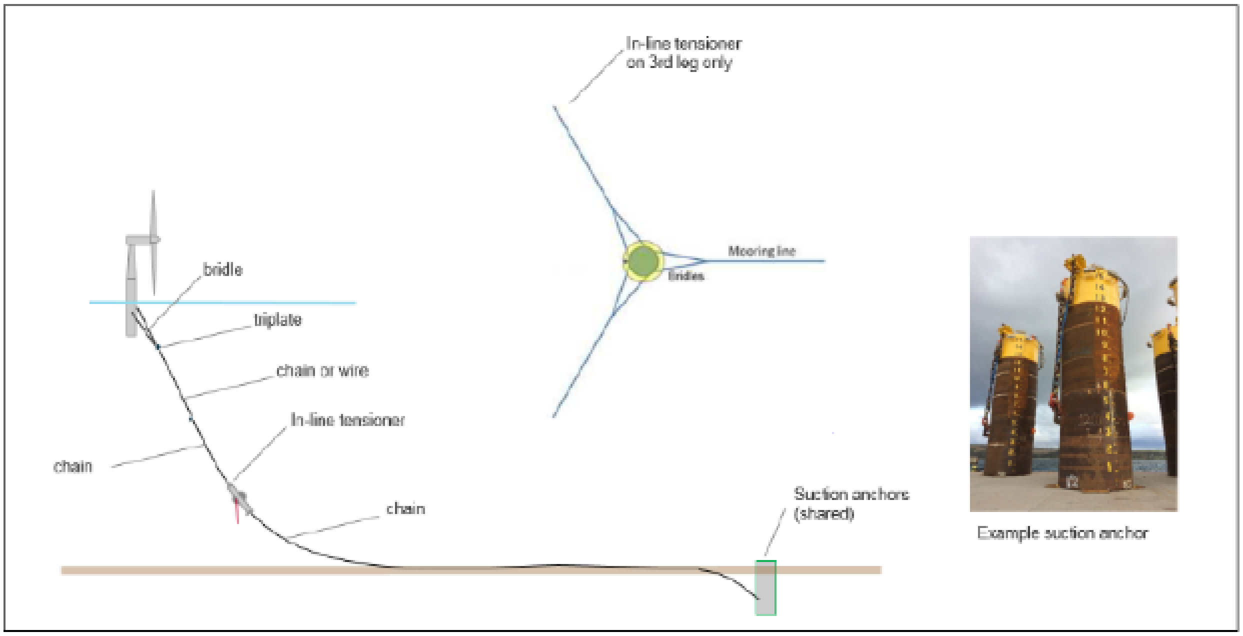


Figure 59 Hywind Tampen anchoring system (Equinor, 2019)

5.1.4 Mitigation

The common fishing impacts found in the FOWT project assessments are that certain fishing activities would need to be excluded from the vicinity of the floating wind farm site due to FOWTs posing a collision/allision risk to fishing vessels, fishing gear snagging on mooring lines and dynamic power cables floating in the water, and distances between turbines prohibiting larger vessels from entering and certain fishing techniques from being performed.

The FOWT project EAs generally found separate impacts on fishing activities during the Construction/Decommissioning stages versus the Operations & Maintenance phases. Construction/Decommissioning phases see relatively higher threats of collision/allision risk due to the number of work vessels working in the area, while the Operations & Maintenance phase sees a relatively higher threat of snagging of fishing gear on cables and mooring lines.

Based on the review of the FOWT project EAs above, the best course of action for minimizing the impact of FOWTs on fishing activities may be to site wind energy lease areas outside of major fishing grounds. If fishing is excluded from areas without much fishing density, then the impact of excluding fishing is minimal. There is a smaller displacement effect, and in turn, a smaller strain on other fishing grounds to which displaced fishermen migrate. The three UK FOWTs were each actively sited in areas outside of heavily fished waters, with Dounreay being built in an area with fishing activities already excluded due to the proximity to a nearby nuclear site (Dounreay, 2016). Figure 60 shows the average value of fishing landings around the Kincardine Windfarm site (denoted in pink) in the years before it was built.

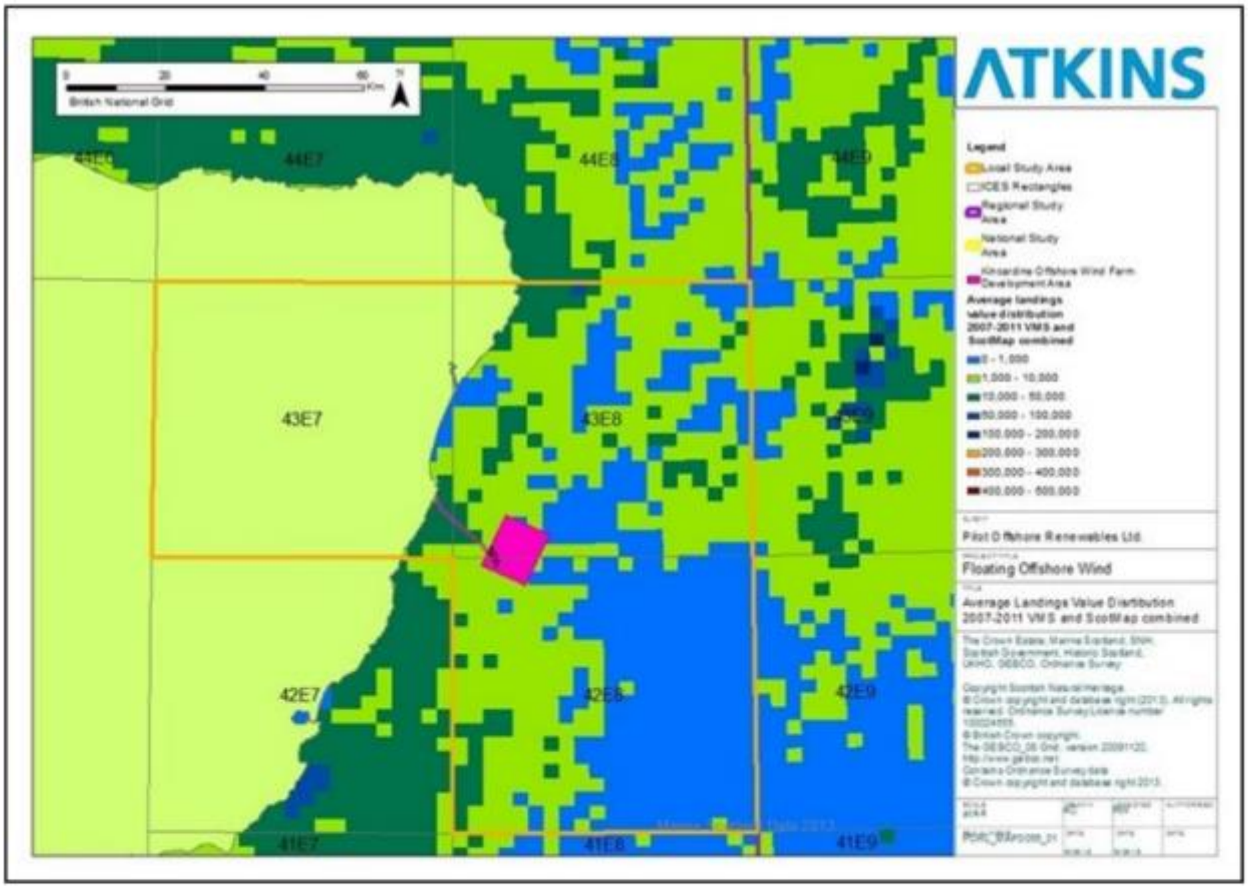


Figure 60 Average Landings Value Distribution,2007-2011 (Kincardine, 2016, pg. 575)

Figure 61 shows the value of landings surrounding the Hywind Scotland site (denoted in red) in the years before the FOWT was built.

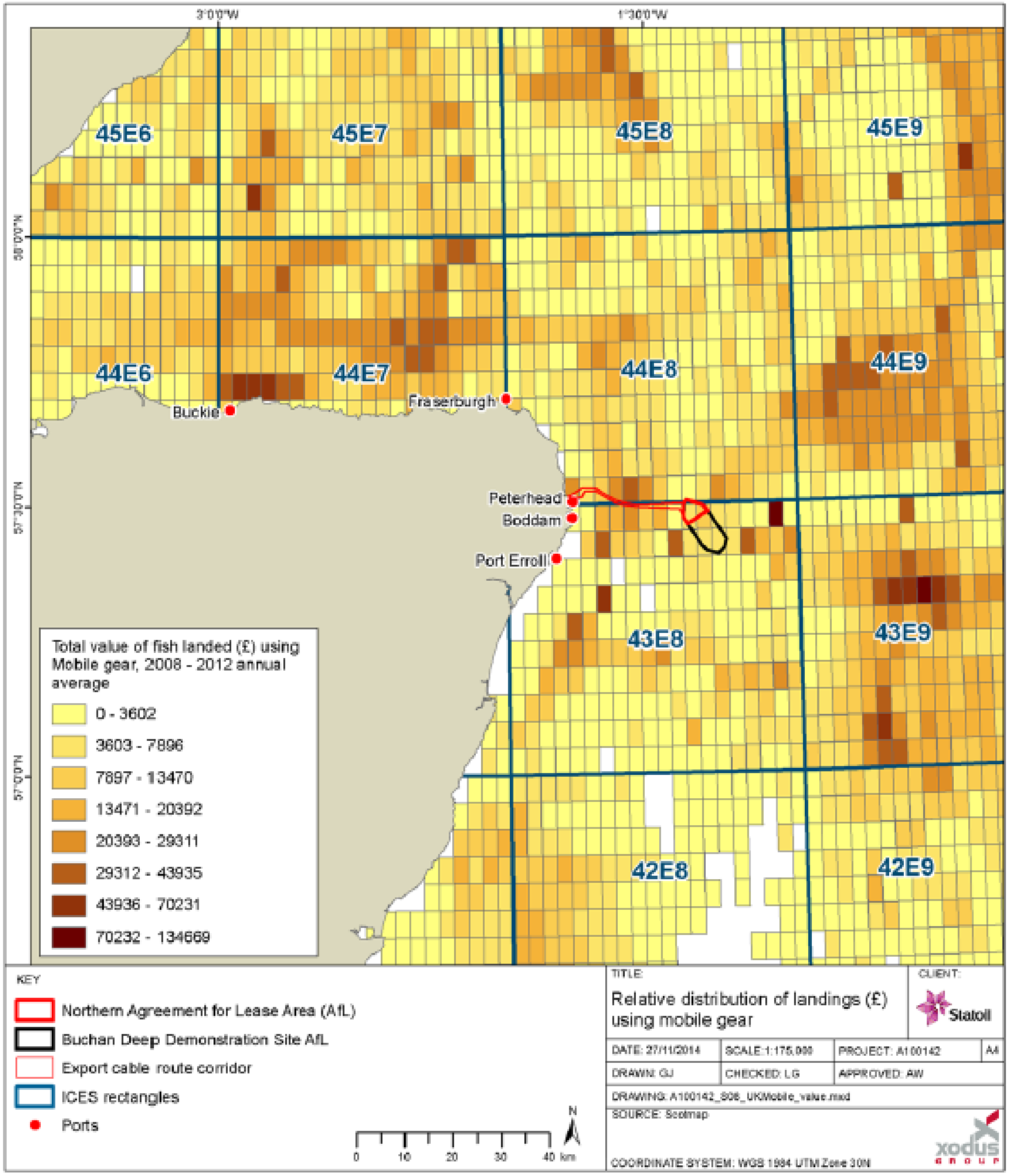


Figure 61 Relative Value of Fish Landed Using Mobile Gear, 2008-2012 (Statoil, 2015, pg. 14-6)

Figure 62 displays the value of landings in the areas surrounding Dounreay (denoted by the black-outlined square) in the years prior to its construction, both overall and by gear type.

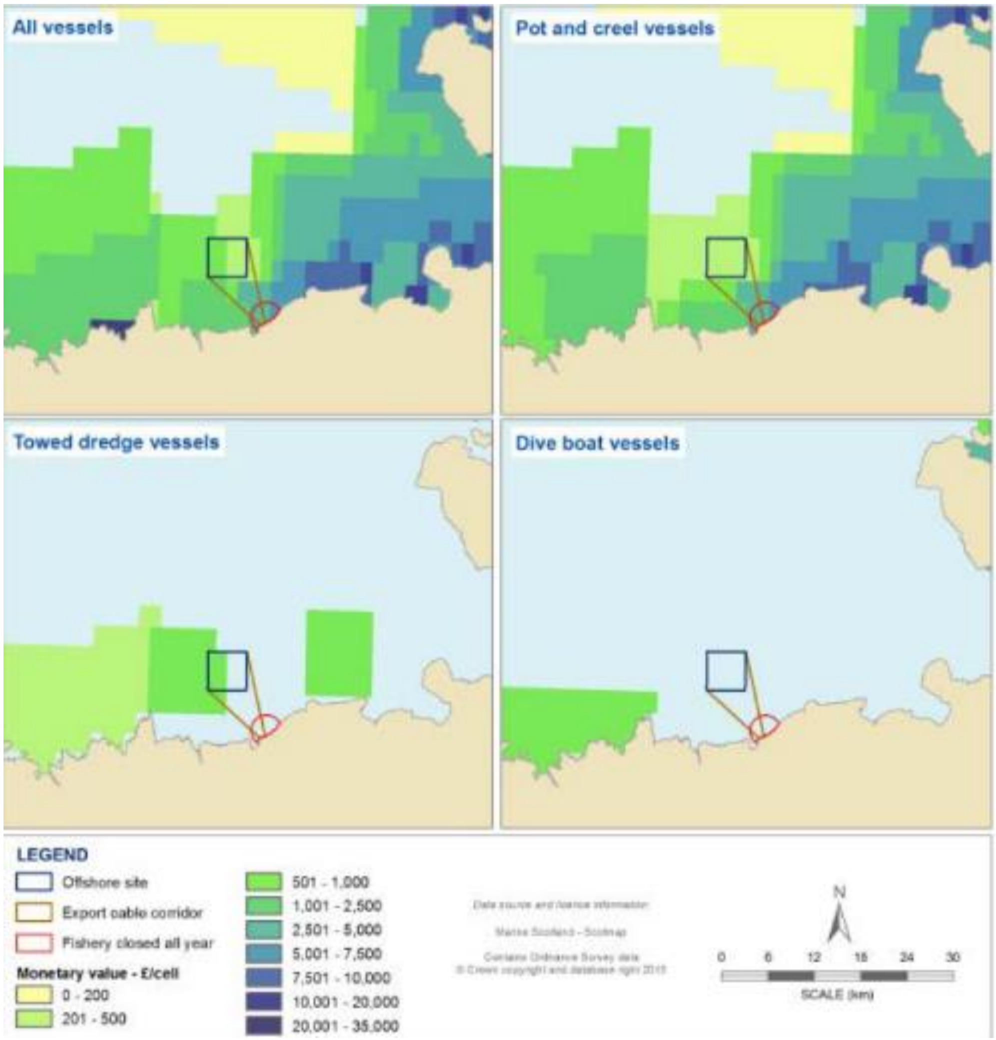


Figure 62 Monetary Value of Fish Landings by Gear Type, 2014 (Dounreay, 2016, pg. 325)

As is readily apparent from the figures, all three FOWT project sites in the UK deliberately chose waters outside of heavily fished areas. While some fishing took place nearby all three project sites in the years prior to projects being established, Kincardine and Hywind Scotland, more so than Dounreay, there was substantially less fishing density inside of the areas chosen for sites and exclusion zones than outside of them. As such, the impact on fishing of the construction of these FOWTS was relatively low, and the displacement effect was minimized.

While fishing exclusion may likely be necessary for safety reasons, it is unlikely to be sufficient for ensuring the safety of fishing near the site. Some other actions recommended by the European EAs to avoid snagging or collision/allision risk include:

- Providing ample information to local fisheries, ports, and other stakeholders about the location and working of the FOWT (Statoil, 2015)
- Regular inspection and maintenance of the turbines, mooring lines, and cables (Kincardine, 2016)
- Burial of cables (Dounreay, 2016)
- Making cables over trawlable (Equinor, 2018)
- Use of metal chains/wires rather than rope for mooring lines (Equinor, 2019)
- Inclusion of turbine location information in sailing directions and almanacs (Statoil, 2015)
- Automatic Identification Systems (AIS) traffic monitoring from an onshore station, to be able to identify ships in or heading for danger (Statoil, 2015)

The Hywind Tampen impact assessment included a consequence to fisheries assessment (Acona, 2018). The fisheries assessment provided information on how other countries manage fishing relative to offshore wind farms:

> In the Netherlands, there is a total ban on shipping within offshore wind farms. In the UK, there is not such a general prohibition, but there are requirements for risk-based assessment of the need for restrictions. In Germany, differentiation is made between the size of the vessel. In all countries that allow traffic in and around the offshore wind farm, the use of passive fishing gear is permitted. Use of active gear such as bottom trawling is prohibited mainly for safety reasons due to submarine cables and other infrastructure. There is little documentation of the extent to which restrictions lead to consequences for fishing interests, but surveys in some facilities show that the development of offshore wind has not had significant consequences.

The impact assessment (Equinor, 2019) described in the previous section, found that fishing in and around the FOWT site using bottom trawl, purse seine, and other bottom-dragging fishing gear was recommended to be excluded with a 500-meter safety zone around the site.

The Hywind Tampen wind farm impact assessment provides strategies to minimize impacts on fishing:

- Submarine power cables being made over-trawlable
- Provide information in advance of the activities to Norwegian and British fishing interests
- Use of chains/wires rather than polyethylene ropes for mooring FOWTs. Mooring ropes with lower densities can float above the seabed and cause a hazard to fishing gear and navigation
- Survey of cable routes after installation to map the extent and position of any free-floating spans and stone fills with the mapping provided to fishermen
- Strive for trawlable anchoring system where technically possible
- In consultation with the authorities, consider the establishment of a trawl-free zone to maintain the safety around the FOWT site

The Fukushima FORWARD project information (Fukushima Offshore Wind Consortium, n.d.) does not address current fishing practices but provides mitigation strategies for fishing in FOWT sites. The project organized a committee of government and fishermen's union members to study the impact on the sea and fishery operations around the project after the installation of FOWT and investigate new fishing methods for future collaboration between the FOWT industry and fishing industry. The research included using remote operated vehicles to observe fish around FOWT structures and moorings. The new methods include marine farming, marine fertilization and culture raft, artificial reefs, and providing real-time information from equipment on FOWT to the fishing industry. Figure 63 and Figure 64 provide graphics of the research and new fishing methods being researched.

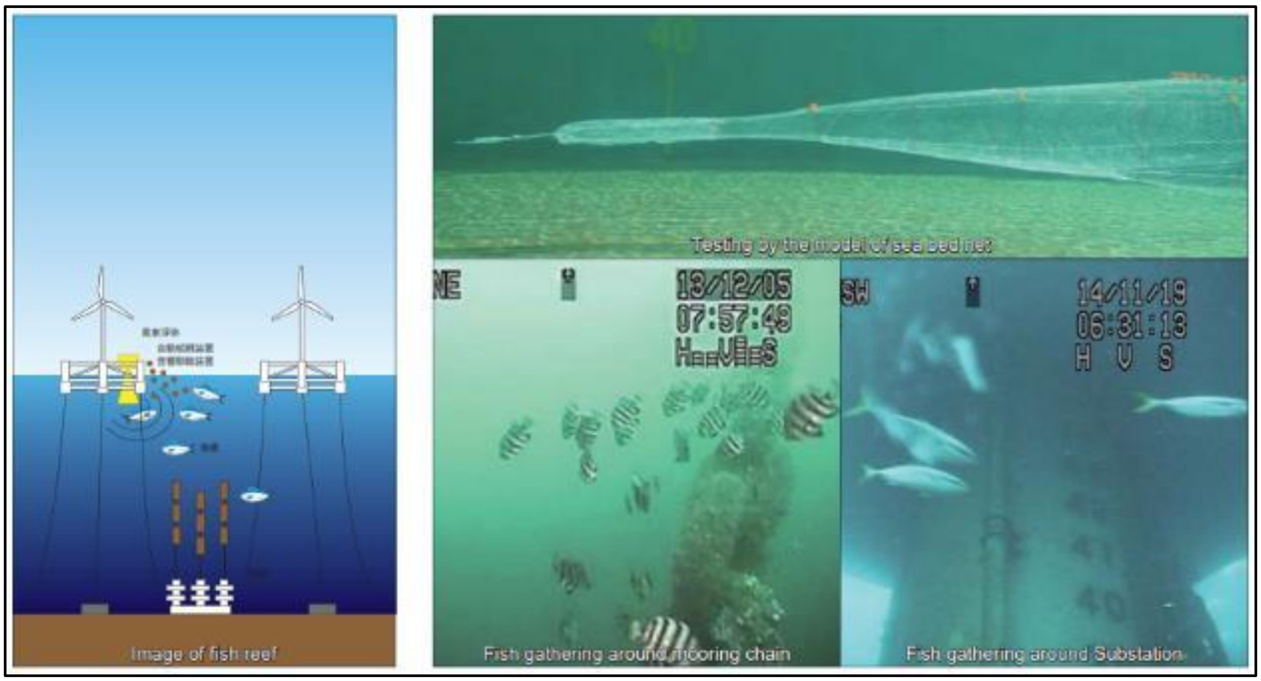


Figure 63 Fukushima FORWARD Collaboration with Fishery Industry (Fukushima Offshore Wind Consortium, n.d.)

1 Proposal for new fishing method	
Items	Scopes
Marine farm	· Construction of new fishery farm by automatic feeder, sound and fishing bank using floater and mooring
Marine fertilization and culture raft	· Cultivation of shellfish and seaweed by marine fertilization through water pumping of deep sea by density diffusion equipment and marine fertilizer
Fish gathering effect	· Observation of fish gathering around floater by ROV
Sea information	· Providing of real time sea information through observation equipment on floater to fisherman and disaster control center

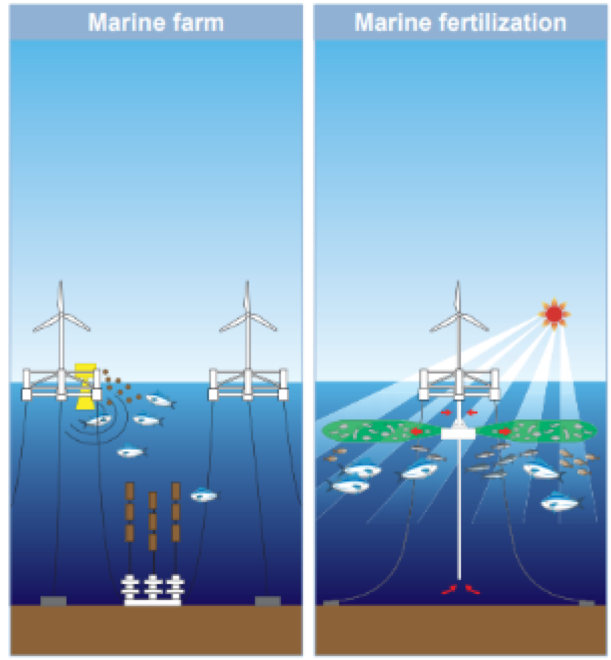


Figure 64 Fukushima FORWARD new fishing methods (Fukushima Offshore Wind Consortium, n.d.)

BOEM should consider conducting further studies to identify fishing areas in and around current and future Call areas and assess potential impacts to fishing. The research should include types of fishing that occurs, species targeted, fishing gear used, depths fished using certain gear, and space required for the types of fishing.

BOEM should coordinate with NOAA Fisheries, USCG Waterways Management, state fisheries, and the fishing industry using all available means, including AIS/NOAA Fisheries Vessel Monitoring System (VMS) data, vessel trip reports, and other fisheries information to determine fishing transit routes and high- and low-density fishing areas and impacts of fishery displacement.

BOEM should collaborate with wind farm developers, NOAA, state fisheries, and the fishing industry to research wind farm designs and fishing methods that accommodate fishing within wind farms.

5.2 NAVIGATION/SHIPPING IMPACTS

5.2.1 Overview

ABSG reviewed available shipping and navigation assessment information from existing FOWT projects to determine how a FOWT site in the OCS would potentially impact U.S. coastal and international shipping. Available information included the EAs for Kincardine (2015), Hywind Scotland (Statoil, 2015), and Dounreay (2016), Hywind Tampen (Equinor, 2019), and the Fukushima FORWARD project. The following section details the review of these FOWT projects' impact assessments to navigation and shipping and potential mitigation strategies that may be applicable to BOEM Call and WEA siting and the development of FOWT projects.

5.2.2 Review of Existing FOWTs/Recent Research Efforts

The Kincardine (2016), Hywind Scotland (Statoil, 2015), and Dounreay (2016) projects assessed the FOWT impact on shipping routes and navigation as they did issues related to fishing: by evaluating the risk posed at each stage of the FOWT lifecycle. The Kincardine assessment found that in all three stages of the project: Construction, Operation & Maintenance, and Decommissioning, shipping and navigation routes are necessarily rerouted (Kincardine, 2016). During the Construction and Decommissioning phases, the presence of work vessels and heavy construction required creating a "safety zone" through which vessels unrelated to the FOWT were not allowed to travel. During the O&M phase, the physical size of the turbine precluded traveling through it for ships and required finding alternative routes.

The designers of the Kincardine FOWT anticipated an exclusion zone of 500 meters around the project site due to the subsea hazards associated with the mooring systems and power cables and chose a deployment area away from heavy shipping routes. The Kincardine wind farm's Operation and Maintenance port is located at Aberdeen Harbor, which has a high density of shipping traffic. The Kincardine designers used AIS data to identify a less traversed area for deployment. Figure 65 shows the AIS data analysis identifying where in the vicinity of the heavily used Aberdeen Harbor shipping is relatively low. Note that the yellow immediately next to the port reflects the densest levels of shipping, and the surrounding green area reflects the next highest levels of shipping density. The Kincardine FOWT, depicted as a purple square, is removed from the yellow and green in the relative low-density blue and dark blue areas.

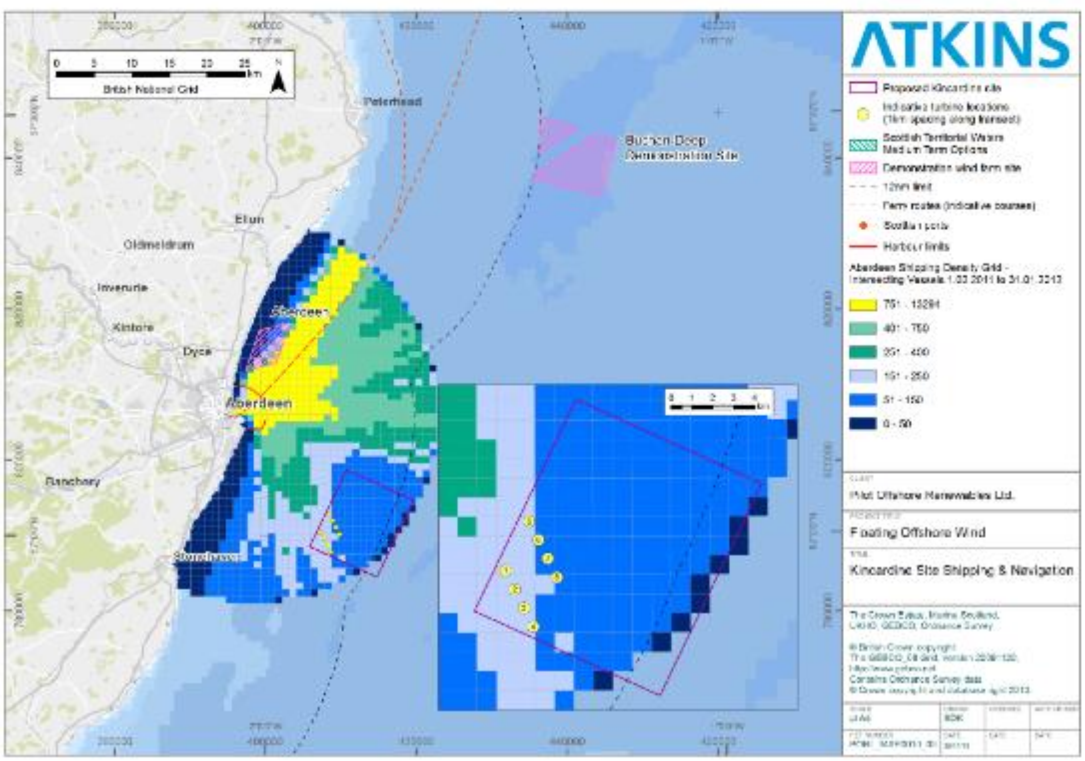


Figure 65 Shipping Density Around Aberdeen Harbor (Kincardine Scoping, 2014, pg. 112)

The Hywind Scotland and Dounreay EAs reached similar conclusions: that shipping and navigation would need to be excluded due to collision and allision risk. Hywind Scotland's assessment examined AIS data from 2014, examining the different types of vessel trafficking in the area being studied for FOWT deployment. Figure 66 displays the location of the Hywind-Scotland project, denoted by black WTG icons surrounded by a red polygon, relative to overall shipping traffic in the vicinity. As is readily apparent, the FOWT site itself is located outside of the heaviest traffic.

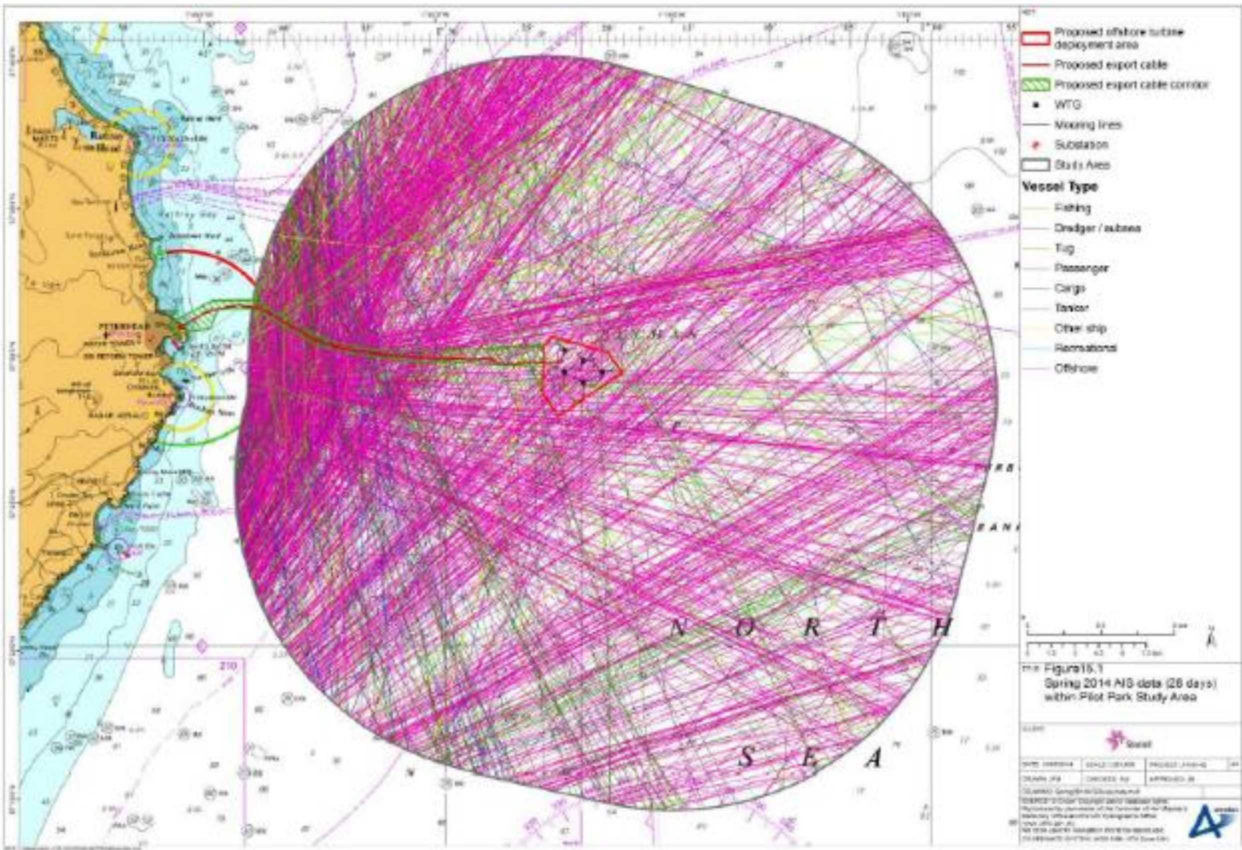


Figure 66 Hywind-Scotland Shipping Traffic (Statoil, 2015, pg. 15-7)

The Dounreay EA similarly examined AIS data for 12 months from 2014 to 2015 and cited the project in an area with relatively lower shipping density. Figure 67 shows that the Dounreay project was deliberately placed outside of where AIS data indicates the heaviest shipping traffic:

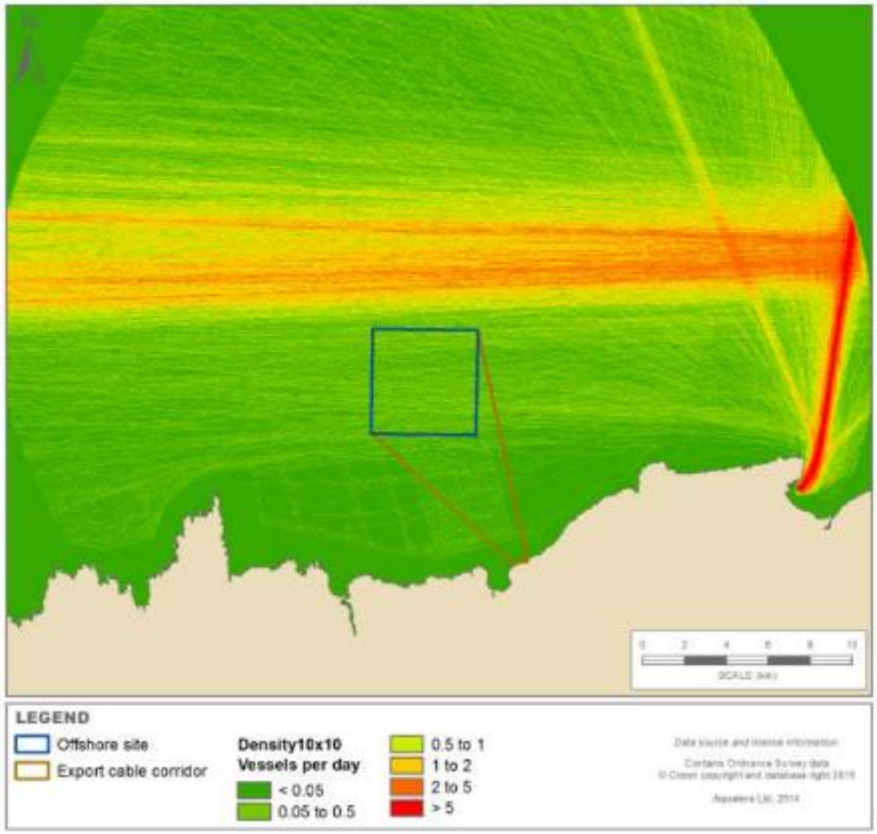


Figure 67 Dounreay Shipping Traffic (Dounreay, 2016, pg. 357)

The Hywind Tampen project is in a North Sea Oil Field to provide power to two nearby oil rigs. Vessel traffic in the area consists mostly of offshore supply vessels (OSV), shuttle tankers, and fishing vessels. The impact assessment found that an average of 2.5 trips per day occurred in the area, and about 15 to 25 tankers pass through the area within a year. Figure 68 shows all vessel transits, including OSVs, tankers, cargo ships, and fishing vessels in the Tampen area for May 2015, with the 11 FOWTs in light green. The impact assessment found that the development of the FOWT site could require some modification of existing tanker transit routes, and Equinor would consult with the companies impacted on modifying the routes (Equinor, 2019).

The risk of collision was assessed at the same low-risk level of the oil rigs in the surrounding area, which requires monitoring of vessel traffic in the area by Equinor's operations center that can contact vessels on a collision course with the wind farm. The impact assessment determined that the probability of collision with a FOWT will depend on the type of safety zone established at the wind farm. The impact assessment also determined the consequence of a collision with a FOWT is less than a collision with a fixed-bottom turbine as the energy from the collision is converted to kinetic energy in the form of the FOWT moving away from the impact, thus reducing impact damage to the vessel and FOWT. The smaller the vessel in relation to the FOWT, the less collision energy is converted, and the collision is similar to a collision with a fixed bottom turbine. Lastly, submarine collision risk with the mooring chain was assessed with the finding that the mooring chain provided sufficient noise to be intercepted by the submarine, and no mitigation was needed. (Equinor, 2019).

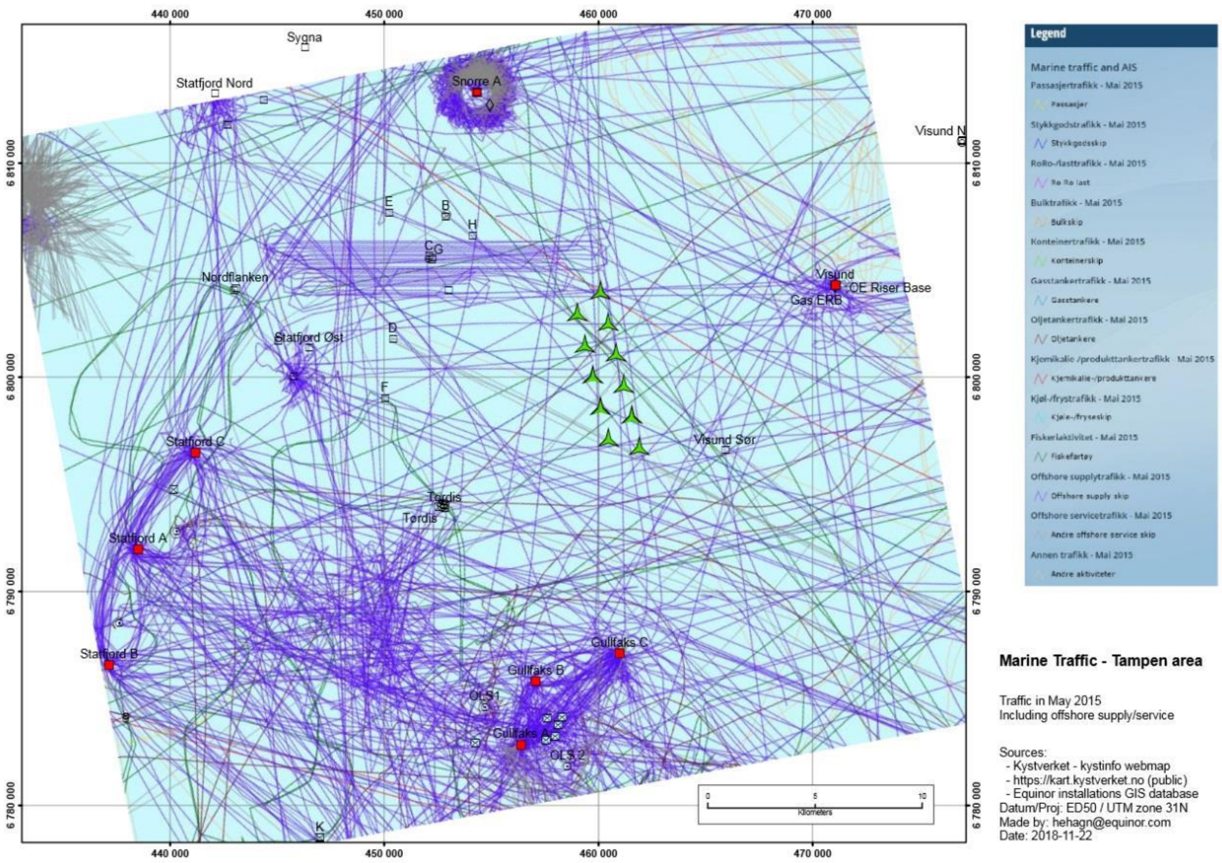


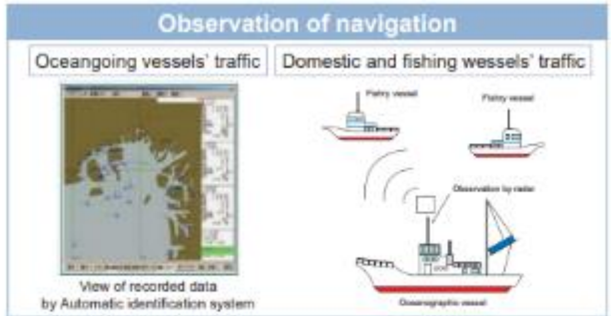
Figure 68 All vessel transits on the Tampen field in May 2015. (Equinor, 2019)

The Fukushima FORWARD project considered collisions between ships or collisions between ships and FOWTs (Fukushima Offshore Wind Consortium, n.d.). Vessel transit data was collected using AIS data and navigation radar surveys at the Fukushima site. A quantitative collision risk model was developed for the site to determine the risk based on the vessel transit data. The result of the risk assessment is used to develop safety measures.

The project also assessed the risk of a drifting FOWT mooring failure due to severe storms or accidents colliding with other FOWTs or vessels. A simulation method based on the actual response of floating turbines was developed, and the consequences of drifting of floating turbines were confirmed.

The collision, initiation of drifting, and drifting behavior of vessels and FOWTs were investigated in wave basins. Analysis code of Rotor-Floater-Mooring coupled analysis code was improved to investigate the response of mooring line in shallow water. A risk evaluation procedure of chain drift was developed based on the risk scenario combined with a chain drifting simulation method. Figure 69 provides a graphic of the navigational impact assessment performed by the Fukushima FORWARD project (Fukushima Offshore Wind Consortium, n.d.).

1	Assessment of collision risk
Items	**Scopes**
Collision risk analysis and risk control option	· Quantitative risk analysis for collision based on risk model and traffic data · Adoption of appropriate risk controloption (safety measures)
Collection of traffic data in the coast area	· Analysis of oceangoing vessels' traffic by AIS data. (past and daily data) · Observation for domestic and fishing vessels' traffic by Rader.



2	Assessment of drifting risk
Items	**Scopes**
Response of moored floating offshore wind turbine	· Development of analysis method of low frequency, wave frequency and high frequency motion of moored floating offshore wind turbine.
Analysis method of drifting risk of floating wind turbine	· Development of a simulator for risk analysis of drifting floating offshore wind turbines considering coupled response of a floater, a wind turbine and a mooring system.

Figure 69 Fukushima FORWARD navigation safety assessment

5.2.3 FOWT Mooring Systems and Dynamic Power cables impact on navigation and shipping.

During this study, we did not identify projects with floating dynamic power cables suspended in the water column between turbines. In all the current projects, the power cables are anchored and buried between turbines. The Hywind Tampen project, with a depth of 260- 300 meters, has the power cables anchored to the seabed 400 to 500 meters from the FOWT and buried. The depth of free-floating sections of power cables was not provided in the impact assessments. The spread of the mooring chain is 800 meters, with 600 meters resting on the seabed (Equinor, 2019). A study by the PNNL on whale encounter with FOWT mooring lines and dynamic power cables provides a depth for the power cables of 100 to 150 meters based on the depth of fishing activities, design economics (deeper cable = more cable = higher cost), and industry input to the Bureau of Ocean Energy Management (Copping and Grear, 2018).

As FOWT projects move into deeper waters, developers will determine the need for floating dynamic power cables floating between turbines and electrical substation platforms based on parameters such as water depth, power loss, and expense. The designs will need to consider the safety of navigation, fishing activities, and vessel traffic as a part of that design.

BOEM should ensure that developers consult with the U.S. Coast Guard and waterway users to consider project-specific factors, such as vessel traffic patterns and fishing activities that occur in and around the FOWT project sites, to inform the design of mooring systems and dynamic power cables to minimize navigation impacts.

5.2.4 Mitigation

Commercial shipping vessels transiting on coastal voyages and trans-ocean voyages follow established routes that provide the most direct route that avoids hazards and adhere to U.S., state, and international regulations such as the Clean Water Act (CWA) and International Convention for the Prevention of Pollution from Ships (MARPOL). Due to CWA and MARPOL requirements, coastal transit routes for commercial shipping are generally greater than 12 nautical miles offshore.

Some of these major shipping routes are within established Safety Fairways and Traffic Separation Schemes (TSS) as codified in Title 33, Code of Federal Regulations, Parts 166-167, established by the U.S. Coast Guard at the entrances to major ports, such as LA/LB, Port Hueneme, San Francisco, and the Straits of Juan De Fuca on the West Coast. The purpose of safety fairways and TSSs is to provide access routes and unobstructed approaches for vessels to and from U.S. ports.

Figure 70 shows the major commercial tanker and cargo vessel coastal and international transits for the west coast of California between the ports of San Francisco and Los Angeles/Long Beach and the BOEM Morro Bay and Diablo Canyon Call Areas. The TSSs for San Francisco and Los Angeles/Long Beach are shown in Magenta in the top and bottom of the figures, respectively. The blue lines represent 2017 AIS tanker and cargo vessel transit count data. The figure is extracted from the Marine Cadastre National Viewer page on the MarineCadastre.gov website.

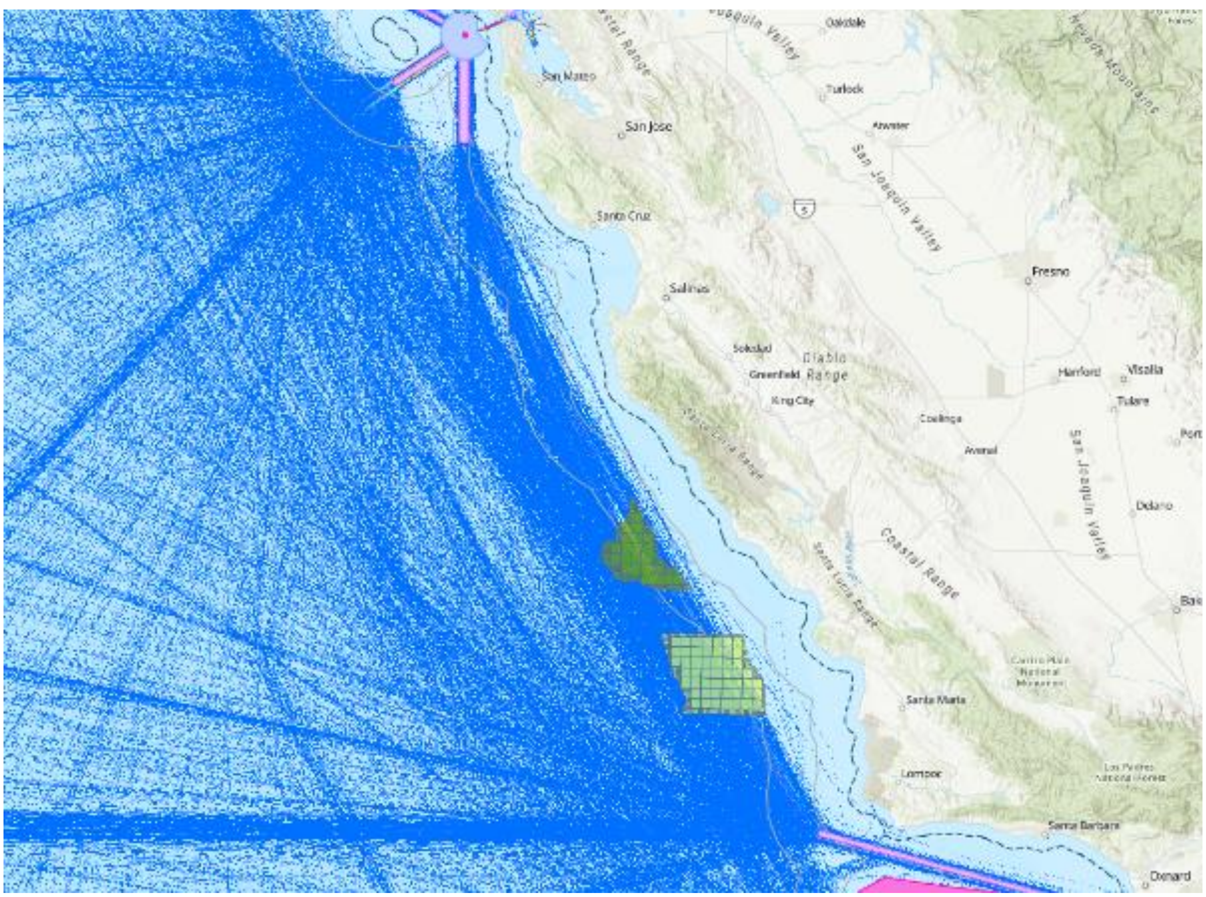


Figure 70 Cargo and tanker vessel transits off the coast of central California (MarineCadastre.gov)

Figure 71 shows the 2017 commercial tanker and cargo vessel coastal transits off Morro Bay, CA. Figure 72 and Figure 73 illustrate the 2017 commercial tanker and cargo vessel coastal transits off northern California, showing the Humboldt Call Area, and Oregon and Washington, respectively. As shown in the figures, some locations on the maps have fewer shipping routes than others.

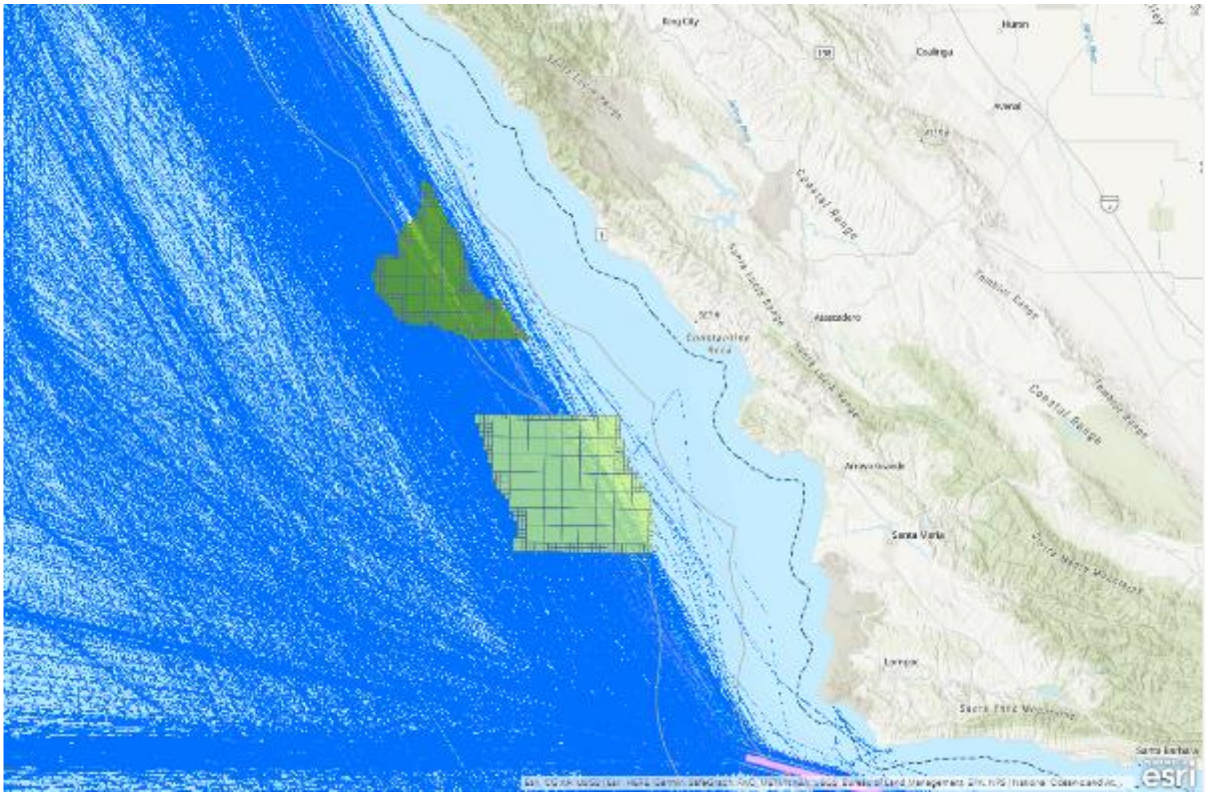


Figure 71 Cargo and tanker vessel transits off the coast of Morro Bay, CA (MarineCadastre.gov)

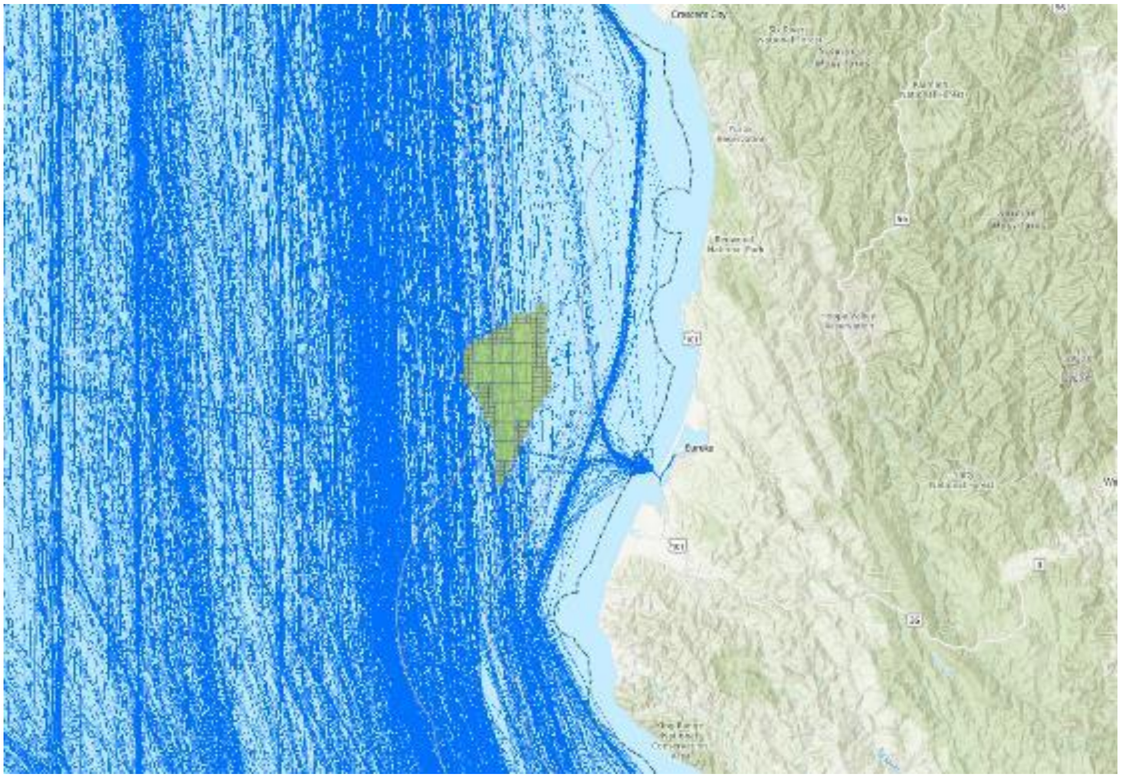


Figure 72 Cargo and tanker vessel transits off the coast of northern California (MarineCadastre.gov)

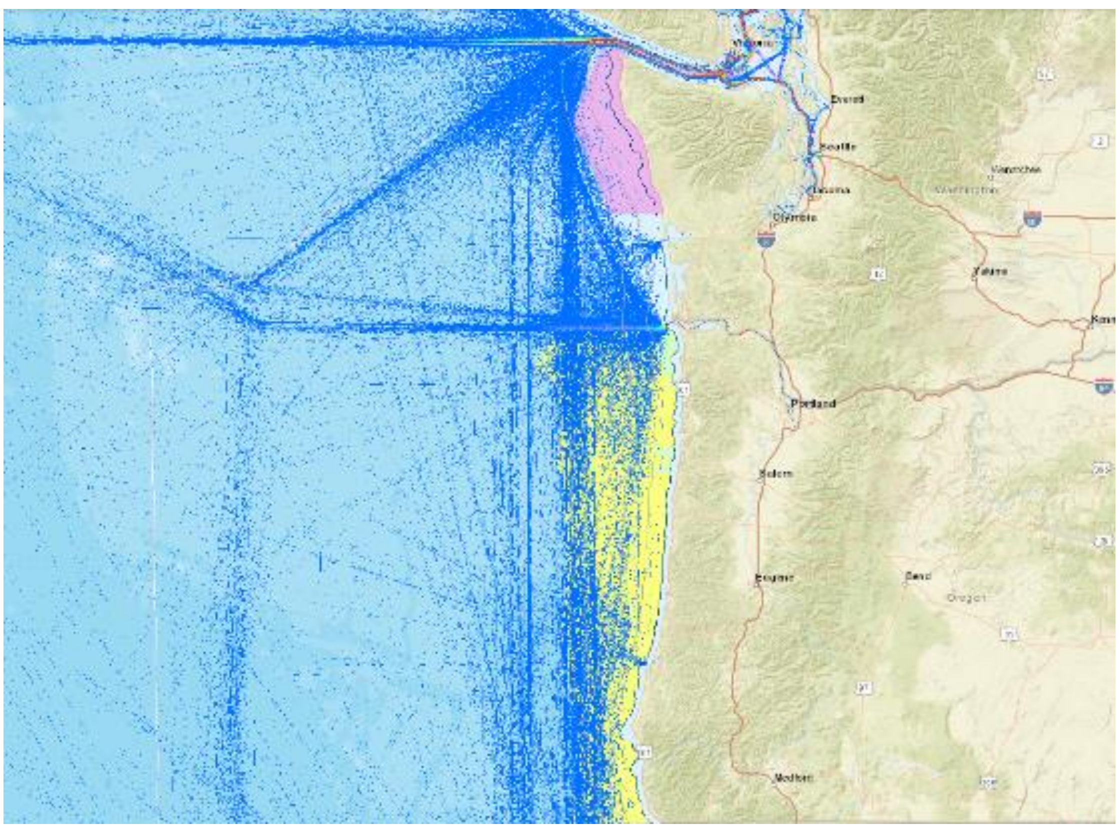


Figure 73 Cargo and tanker vessel transits the coast of Oregon and Washington (MarineCadastre.gov)

Figure 74 shows the Oahu North and Oahu South Call Areas and all vessel transits around Hawaii. 2017 AIS vessel transit data for Hawaii is not available on the Marine Cadastre National Viewer, 2019 transit data is available on the viewer, although the data is not categorized by vessel type.

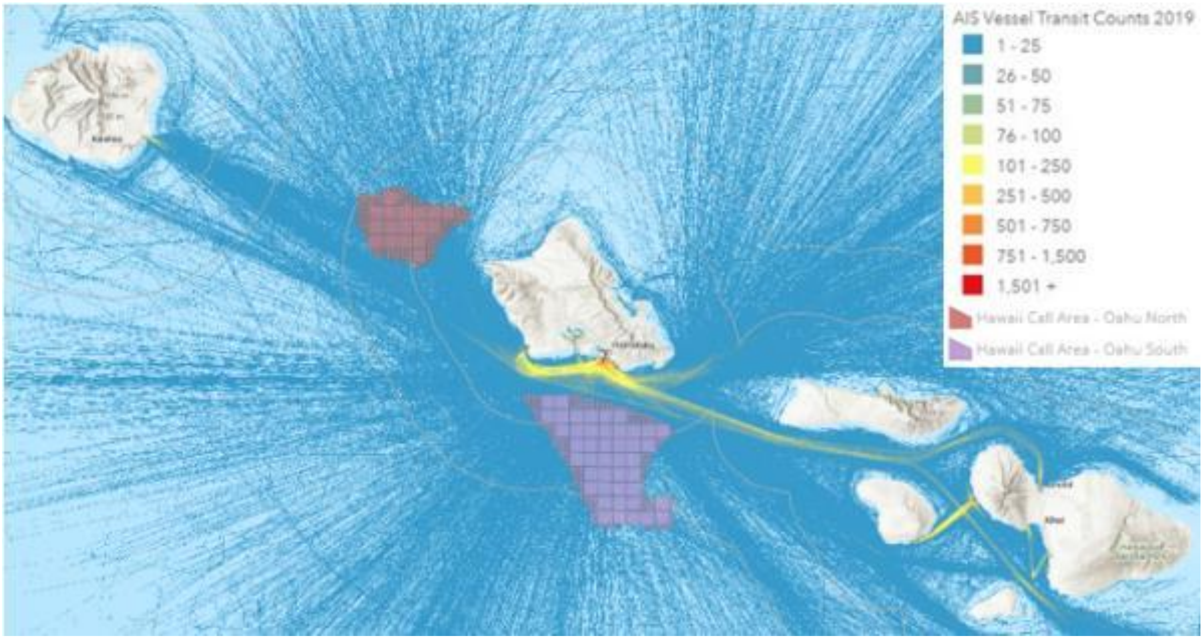


Figure 74 All vessel transits off Hawaii (MarineCadastre.gov)

The state of Maine intends to file an application with the BOEM for a floating offshore wind research array, located in the Gulf of Maine, to advance new technology in collaboration with Maine's fishing industry. As envisioned, the research array would be located some 20 to 40 miles offshore into the Gulf of Maine, in an area that would allow a connection to the mainland electric grid in the southern half of the state. The research array is expected to contain a dozen or fewer FOWT in the 10 to 14 MW range over approximately 16 square miles of ocean or less (State of Maine, 2020).

As of February 2021, Maine is conducting stakeholder engagement with the fishing industry and other stakeholders to determine the site for the 16 square mile research array project. The state also has an interactive siting map showing the potential area for siting the project with the area bounded by a solid red line, as shown in Figure 75. The figure also shows the DoD wind exclusion areas in solid red and the federally regulated southern and eastern TSSs that provide access routes for vessels to and from the port of Portland, ME. Figure 76 illustrates the potential area for siting the project overlayed on an extract from the Marine Cadastre National Viewer showing 2017 AIS vessel transits for cargo, tanker, and tug & tows in the Gulf of Maine and the DoD Offshore Wind Capability Assessments the wind exclusion areas in red and yellow areas have site specific stipulations. The graphic clearly shows established commercial vessel transit patterns that go through the potential area for siting the project, particularly the routes to the entrances to the eastern TSS, through the TSSs, and the tug & tow route passing through the northwest portion of the potential area.

As Maine refines the site location for the 16 square mile research array project in federal waters, excluding the areas mentioned above would reduce the impacts on commercial vessel transits.

BOEM should encourage the State of Maine to work with USCG Waterways Management on vessel traffic and safety of navigation issues as the state seeks to identify the specific site for the proposed research array to avoid impacts to navigation and shipping.

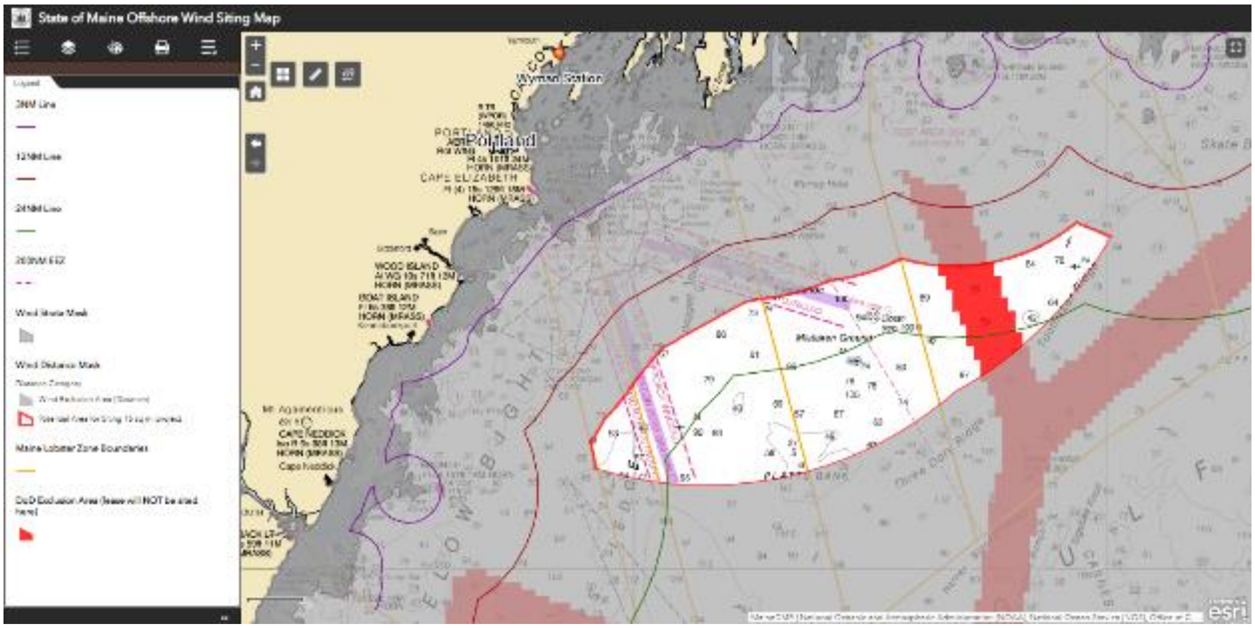


Figure 75 State of Maine Offshore Wind Siting Map (State of Maine, 2021)

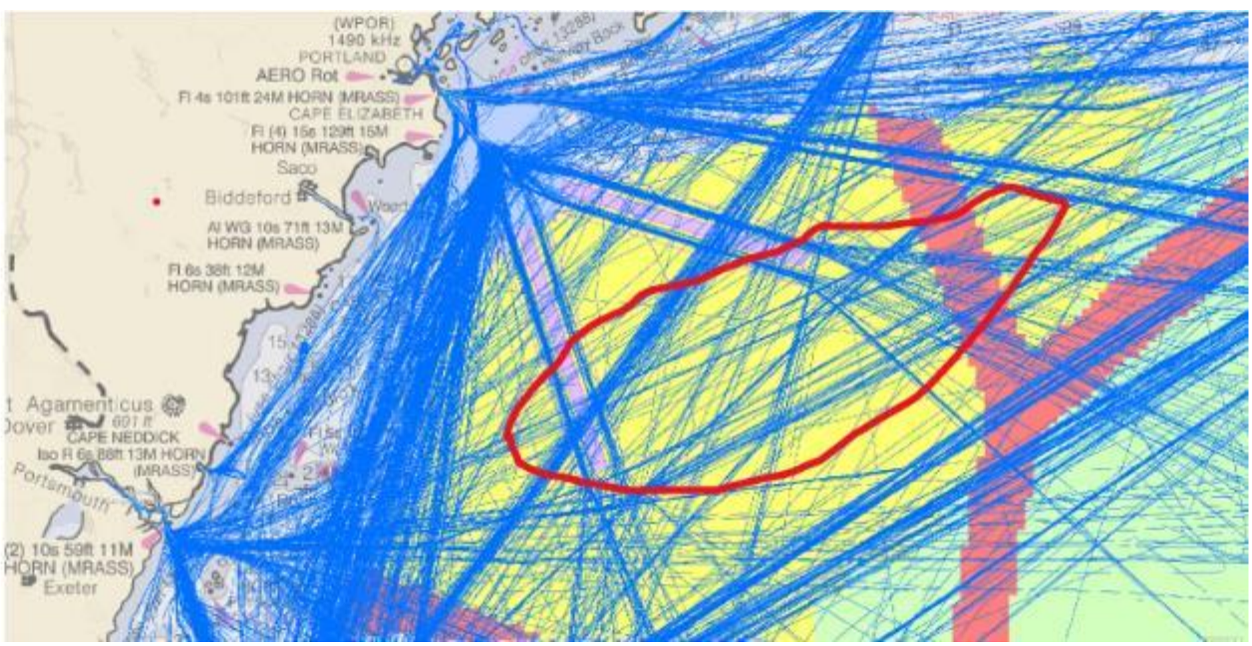


Figure 76 Cargo, Tanker and Tug&Tow vessel transits in the Gulf of Maine (MarineCadastre.gov

The main risks to commercial shipping traffic include allisions with FOWTs and collisions with support vessels, particularly if the FOWTs are near each other. Navigation risks are reduced for smaller vessels that are able to operate among FOWTs within a wind farm, but they will still need to consider navigation hazards due to moorings and floating dynamic submarine cables. A prudent mariner is most likely to navigate around the wind farm and not put the vessel at risk of allision in a close-quarters situation with FOWTs or risk of collision with other vessels within the wind farm.

The EAs for the existing FOWT sites in the UK recommended mitigation methods for collision and allision risks applicable to all phases of the lifecycle:

- Live AIS traffic monitoring from an onshore station, with a procedure to be followed should a ship be on a collision course
- AIS broadcasts from work vessels
- Sailing directions and almanacs circulated to the relevant organizations, with information being given directly to local ports and ship operators
- Operational safety zones
- Appropriate markings/lighting
- Full information on FOWT locations to maritime stakeholders

Hywind Tampen recommended mitigation measures for shipping/navigation impacts include:

- Excluding large vessels from the FOWT site and modifying routes around the site
- The wind farm will be marked on all relevant charts
- The position of the wind turbines will be monitored by the wind farm's operations center that will receive an alarm and position if the FOWT moves outside a given position (e.g., mooring line breaks)
- Vessel traffic will be monitored and notified if on collision course with FOWT by the operations center with radar located in FOWT

BOEM should request the USCG Waterways Management conduct Port Access Route Studies (PARS) for central and northern California, Oregon, Hawaii, and the Gulf of Maine to identify and analyze current maritime traffic, routes, and vessel traffic densities to determine the potential impacts from offshore wind development. BOEM could use the results of the PARS to evaluate current and future Call areas and WEAs, including the proposed Maine floating offshore wind research array.

5.3 PELAGIC LIFE IMPACTS

5.3.1 Overview

ABSG reviewed EAs of existing FOWT projects and other analyses to gauge the likely impact of FOWTs on pelagic species, particularly the potential impacts of mooring lines on marine mammals. Kincardine (2016), Hywind Scotland (Statoil, 2015), and Dounreay (2016) environmental assessments identify four key issues posing risks to pelagic life:

- Entanglement risk to marine mammals from mooring lines and inter-array/export cables, mainly during the Operations & Maintenance phase (Kincardine, 2016; Statoil, 2015; Dounreay, 2016)
- Impacts of accidental chemical spills from FOWT structures on marine mammals and fish, mainly during the Operations & Maintenance phase (Kincardine, 2016; Statoil, 2015; Dounreay, 2016)
- Acoustic damage to marine mammals and fish from noise during the construction of the FOWTs (Kincardine, 2016; Statoil, 2015; Dounreay, 2016)
- Habitat displacement to marine mammals and fish throughout the FOWT lifecycle (Kincardine, 2016; Statoil, 2015; Dounreay, 2016)

The EAs and other research assessed risk for each of the key issues posing potential threats to pelagic life as low risk, finding:

- Entanglement risk tends to be indirect rather than direct. Rather than a marine mammal becoming entangled in a mooring line or cable, it is more likely that derelict fishing gear or debris would become entangled in the mooring line or cable, and a marine mammal entangled in the derelict fishing gear or debris. Measures should focus on reducing the risk of indirect entanglement. (Kincardine, 2016; Statoil, 2015; Dounreay, 2016)
- Chemical spill risks are low risk in small quantities, especially for fish (Morandi et al., 2018). An ABSG report also found that spills in large quantities are highly unlikely from FOWT sites due to the low quantity of oils and chemicals used in offshore wind turbines (ABSG, 2017)
- Acoustic damage tends to be minimal to either marine mammals or fish (Kincardine, 2016; Statoil, 2015; Dounreay, 2016)
- Habitat displacement risk to pelagic species is generally minimal, and impacts on habitats may even be a net positive. FOWTs have a greater artificial reef effect than other types of turbine foundations, leading to higher congregations of fish. Higher congregations of fish attract marine mammals, due to increased opportunity for prey. However, cables may disrupt migratory paths somewhat, and indirect entanglement risk has the potential to compromise marine mammal habitats. (Kincardine, 2016; Statoil, 2015; Dounreay, 2016; Equinor, 2018)

5.3.2 Entanglement

The risk of entanglement to marine mammals exists from mooring lines connecting FOWTs to the seabed, inter-array cables connecting FOWTs to each other, and export cables carrying energy from the FOWT site to shore. FOWTs are uncommon today, and there is little industry experience from which to gauge the seriousness of the entanglement risk to marine mammals from direct entanglement to properly constructed and regularly maintained FOWTs. Additional risk of entanglement for marine mammals is becoming entangled in derelict fishing gear or debris that has caught on FOWT mooring lines or cables.

Experiences gathered from the UK FOWT projects, the Aqua Ventus project in the Gulf of Maine, and research by the PNNL, together with other relevant studies, are reviewed and summarized on the entanglement risks.

In considering the local paucity of large whale occurrence in the area, the UK Kincardine (Kincardine Scoping, 2014), Hywind Scotland (Statoil, 2015), and Dounreay (2016) EAs indicate little risk of direct entanglement to marine mammals from mooring lines and cables. Mooring lines and cables are constructed to be taut with very little slack, the assessments found, significantly reducing the likelihood of entanglement. The buoyancy of the platforms and the size of the anchors help maintain taut cables and mooring. Even if a marine mammal were to allide with cables or mooring, that a marine mammal is unlikely to become entangled (Statoil, 2015).

Indirect entanglement with mooring lines and cables was found by the EAs to pose a serious risk to marine mammals, especially the offshore locations with smaller marine mammals as derelict fishing gear could become entangled in the mooring lines and cables, and marine mammals with the derelict fishing gear. The assessments found that adrift derelict fishing gear may become ensnared on a FOWT mooring line or undersea cable, and "ghost fish" for nearby marine mammals. Smaller marine mammals, in the case of the UK turbines (Statoil, 2015), mainly seals and dolphins, were at high risk from "ghost fishing" gear. Other types of smaller marine mammals in other areas may also be at high risk of indirect entanglement. Regular inspections of the FOWT site to check for and remove the derelict fishing gear that might "ghost fish" significantly mitigates the risk of marine mammal entanglement (Kincardine, 2016).

The University of Maine Volturn U.S. Project (Brady, 2015) studied the direct entanglement risk of marine mammals. The University of Maine deployed the 1:8 scaled FOWT Aqua Ventus in the Gulf of Maine, which delivered power to the Central Maine Power Grid. The turbines and platforms were monitored by web cameras, examining the impacts of the turbine on marine mammals. The marine mammals spotted by the web cameras were seals and porpoises. No entanglement was observed during the monitoring of these mammals. Monitoring could be used as a mitigation of mammal entanglement.

Aqua Ventus also identified ways of mitigating indirect entanglement should extreme weather cause a turbine or part of one to be disconnected from the moorings. Namely, that a synthetic wire/rope or chain mooring lines would be connected to a light mooring rope and "dropped to the bottom of the seafloor" (Brady, 2015, pg. 33), which in turn would be "connected to a floating mooring ball so steel portions of the mooring line could be later retrieved and reconnected to the platform" (Brady, 2015, pg. 34)." The mooring lines are constructed in such a way that if a turbine were separated in some extreme circumstance, the mooring lines would be designed to fall to the seafloor, sparing marine mammals the risk of entanglement.

In 2018, the PNNL conducted a simulation (Copping and Grear, 2018) visualizing the likelihood of entanglement for a mother humpback whale and her calf. A mother and a calf together were assessed to be the likeliest combination of whales that would most likely interact with offshore floating wind mooring systems in the Pacific and were the focus of the simulation. The simulation seemed to indicate that the whales were unlikely to be entangled while swimming on the surface and that they seldom dive more than 120 meters for food. Cables typically are placed 100-150 meters underwater. Deeper placed cables, then, are likelier to prevent entanglements of whales and other marine mammals. Although no quantitative analyses have been undertaken, the simulation seemed to indicate that as in the UK and Maine, the marine mammals potentially are highly unlikely to become entangled directly with mooring lines or cables, assuming they have natural abilities to avoid physical structures and because of the tautness of the mooring lines.

PNNL also confirmed the UK findings that some entanglement risk does exist from fishing gear that has been snagged on the mooring lines or cables. It was presented in Copping et al. (2020) that stakeholders remain concerned for direct interaction, or secondary risk from derelict fishing gear snagged on mooring lines. In addition, according to Copping and Hemery (2020), the potential for mooring lines and cables to become a hazard for marine animals that may become entangled or entrapped in them is uncertain but has been raised by stakeholders. The risk of entanglement with cables and mooring lines in an array of units is not known and should be investigated as arrays are deployed in the future.

The study by Kraus et al. (2014) indicated that visibility is an important factor in mitigating the entanglement risk. According to Kraus et al. (2014), North Atlantic right whales become entangled in gear all the time even though we know that they can see the ropes. Studies reported by Kraus et al. (2014) suggested that changing commercial fishing rope color to red and/or orange may enhance the whale's ability to visually avoid entanglements in the wild. Field trials of orange ropes by a group of Maine lobstermen indicate that switching rope colors in that industry is feasible.

Behavioral state (e.g., transiting, feeding, resting) plays a very important role in how whales respond to external stimuli, according to Robertson et al. (2013) and could be considered as part of future mitigative strategies.

Harnois et al. (2015) performed a case study with six mooring configurations for entanglement risk. It is found that catenary moorings pose a higher risk of entanglement than a taut system, even though absolute risk seems low in this qualitative assessment of risk.

Considering the limited amount of information available on direct entanglement and considering the fast-paced technological developments and varying environments being considered for offshore floating wind, additional research is recommended. However, since current information highlights the risk of indirect entanglement, mitigation strategies should focus on preventing indirect entanglement. The aim of mitigation strategies should be, above all else, to prevent derelict fishing gear from becoming entangled in mooring lines or cables. Mitigation strategies would, per examined research, include:

- Fishing exclusion zones around FOWT sites to reduce the impact of derelict fishing gear from in and around the wind farm site
- Regular inspection of FOWT sites to remove the derelict fishing gear that drifts into the FOWT site and entangles on moorings and cables

- Construction of mooring lines and cables in such a way that should a FOWT structure break away from its mooring or is disconnected for maintenance, the mooring lines, and cables sink to the bottom of the ocean rather than float on or near the surface where a marine mammal might encounter them

5.3.3 Spill Risk

Several chemicals and liquids are involved in the fabrication and operation of FOWTs, all of which may negatively impact fish and marine mammals should they spill. An assessment of potential FOWT sites off the shores of California and Hawaii was conducted in 2018 (Morandi et al., 2018), with analyses performed on the impact of spilled FOWT chemicals on fish and marine mammals. Table 25 lists the findings of the assessment:

Table 25 Adverse Impacts of Chemical Spills on Fish and Marine Mammals (Morandi et al., 2018)

Oil/Chemical Type	Use In FOWT	Potential Adverse Spill Effects on Fish	Potential Adverse Spill Effects on Marine Mammals
Diesel	Fuel	Acutely toxic when directly exposed to spilled material. Small spills in open water dilute rapidly, reducing the likelihood of massive kills.	Direct exposure of sensitive tissues (e.g., eyes, mucous membranes) and inhalation of fumes can lead to temporary irritation and inflammation. Large mortalities are unlikely because of the short amount of time the oil is on the water surface.
Biodiesel	Fuel	Based on available information, not acutely toxic and a low likelihood of large kills.	Based on available information, not acutely toxic and low likelihood of large kills. There is a considerable risk of smothering fur-marine mammals.
Dielectric Insulating Fluids	Electrical Insulation	Based on available information, not acutely toxic with a low likelihood of large kills.	Based on available information, not acutely toxic and low likelihood of large kills. There is a risk of smothering fur-marine mammals.
Sulfuric Acid	Electrolyte	Acutely toxic when directly exposed to spilled material. Small spills in open water dilute rapidly, reducing the likelihood of mass kills.	Direct exposure to sensitive tissues (e.g., eyes, mucous membranes) can lead to temporary irritation and inflammation.
Ethylene Glycol	Dampen motion in offshore wind energy turbines	Acutely toxic when directly exposed to spilled material. Small spills in open water dilute rapidly, reducing the likelihood of mass kills.	Direct exposure to sensitive tissues (e.g., eyes, mucous membranes) can lead to temporary irritation and inflammation.

The fuels and chemicals commonly used in the operation of FOWTs are unlikely to harm fish populations in small spills, either because they are not acutely toxic or because they quickly dilute in open water. Marine mammals tend to be more somewhat vulnerable to spills than fish because they come to the surface to breathe. Fur-marine mammals face an increased risk from spills, as even small quantities of biodiesel are likely to smother them (Morandi et al., 2018). However, most of the chemicals used in FOWTs are not acutely toxic to marine mammals or sea turtles in large quantities and will cause only mild irritation or inflammation if they are spilled in small quantities.

Spills tend to be the result of transportation failures or accidents and from shock events such as hurricanes or earthquakes (Morandi et al., 2018). Best practices should be followed during construction and during transport. Natural disasters are more difficult to defend against since they cannot be predicted. Mitigation measures may include:

- Building FOWTs in areas less prone to hurricanes, earthquakes, and other natural events
- Building FOWTs with hurricane-resistant materials using standards, which minimize natural hazards
- Employing proper lighting and marking
- Equipping boats with oil spill kits (Kincardine, 2016) so that they can assist in clean up should they cause a spill
- Employing best practices and navigational aids help to reduce the likelihood of a spill (Kincardine, 2016)

5.3.4 Noise Impacts

The EAs for the Kincardine (2016) and Hywind Scotland (Statoil, 2015) found only minor noise impacts from FOWTs on fish. The Kincardine assessment found that noise poses more a nuisance than a danger to all species of fish and that the abundance of similar feeding and breeding grounds means that fish can easily go elsewhere to feed or mate. All species looked at by the Kincardine assessment were found to be impacted either negligibly or only in a minor way. The Hywind Scotland assessment had similar findings: fish are more likely to be annoyed than seriously affected by underwater noise. The Hywind Scotland study further found that noise impacts were likely lesser for FOWTs than Fixed-Bottom Offshore Wind Turbines because there are no solid foundations through which energy is transmitted in the water column, and no pile driving is used in its construction.

The Hywind Scotland (Statoil, 2015) and Dounreay (2016) EAs found the same to be true of marine mammals in the vicinity of FOWT construction. The environmental assessment for the Hywind Scotland project (Statoil, 2015) and the Dounreay project (Dounreay, 2016) both found that due to the lack of solid foundations, and lack of monopolies used in construction, that noise damage to marine mammals could only come from work vessels. Each also identified the likely radius around work vessels in which marine mammals would hear the noise, and how long they would need to be exposed to the noise in order to face long-term adverse impacts. The Hywind Scotland assessment found that marine mammals would need to be within 25 meters of vessels for periods of over 24 hours in order to suffer serious or long-term damage from the noise, rendering the risk level effectively null during those phases of the lifecycle. The Dounreay assessment found that a marine mammal would have to be even closer to the work vessels for 24 hours, within as little as 5 meters for some species.

The EAs assessments of negligible noise risk to fish and marine mammals are supported by evaluations performed by the PNNL (Copping et al., 2020), an environmental sensitivity assessment performed by BOEM for Central California and Hawaii (Morandi et al., 2018), and a comparison of environmental effects of different offshore wind foundations by BOEM (Horwath et al., 2020). The PNNL found that only about 10% of vibration noise emitted by the turbine tower would transmit underwater (Copping et al., 2020), and that overall noise would pose only a minor disturbance to fish. The BOEM studies found that FOWTs emit considerably less noise than fixed-bottom offshore wind turbines because pile driving, typically the largest drivers of acoustic impact, is not necessary for their construction (Morandi et al., 2018; Horwath et al., 2020). As such, noise levels are minimal and acoustic impact on fish and marine mammals is negligible.

5.3.5 Habitat Displacement

The final key concern indicated by research regarding FOWT impacts on pelagic life is the potential for the structures to disturb the habitats of marine mammals and fish. Potential issues were primarily related to the possibility of long-term habitat displacement; that is, while a FOWT is in operation, marine mammals and fish would avoid it entirely, eliminating a habitat for them. These concerns stemmed from worries over (Kincardine 2016; Statoil 2015):

- Inability of fish to lay eggs in the vicinity
- Reduction of fish populations
- Reduction of marine mammal populations due to decreased fish stocks
- Interruption of migratory paths

A review of the UK FOWT EAs and recent/ongoing studies on the environmental impacts of FOWTs indicates that these concerns are largely unfounded. While there is some risk of the disruption of migratory paths (Morandi et al., 2018), there is negligible risk of long-term habitat disruption for fish and evidence of net benefits to habitats for both fish and marine mammals due to an artificial reef effect. In particular, the EAs found:

- There is an abundance of similar habitats nearby to which marine mammals and fish can go (Kincardine, 2016)
- Floating objects such as mooring lines and cables have been observed acting as fish aggregating devices (Brady, 2015), in which they function as artificial reefs and actually attract more fish to them. These effects are particularly pronounced with Floating versus Fixed-Bottom turbines (Horwath et al., 2020)
- Increased fish stocks create a more attractive habitat for marine mammals

The Kincardine (2016), Hywind Scotland (Statoil, 2015), and Dounreay's (2016) studies generally found minor or negligible impacts on fish habitats, with little potential for permanent habitat loss. The Kincardine assessment focused on whether fish would be permanently displaced and unable to relocate. They found the fish would be minimally disturbed and could relocate easily. Hywind Scotland examined whether nursery and spawning grounds would be lost to fish with the construction and operation of FOWTs. Uplifting of sediment was not found to be a serious concern, and because of the relatively small scale of the projects, fish could easily relocate if need be. The Kincardine assessment even found that the underwater cables and moorings have the potential to act as artificial reefs, wherein fish would congregate. Overall, risks to fish habitats were assessed to be negligible or minor. The Dounreay (2016) assessment had similar findings, namely that floating structures and associated moorings often act as artificial reefs and fish aggregation devices, attracting fish, and providing a habitat for them.

The EAs reached similar conclusions regarding the habitats of marine mammals. The Kincardine wind farm EA (Kincardine, 2016) examines habitat disturbance in the context of the effect on prey distribution. If a FOWT disrupts the habitat or travel patterns of fish and other animals that marine mammals feed on, then the vicinity of the FOWT is less habitable to marine mammals. The Kincardine assessment finds little risk of a FOWT significantly impacting the location of prey, instead of finding some evidence that the volume of prey species could increase modestly in the vicinity of FOWTs if there is a fishing exclusion zone (Kincardine Scoping, 2014). Marine mammals that eat fish, then, would actually have their habitat enhanced by the presence of the turbines. Hywind Scotland (Statoil, 2015), Dounreay (2016), and Hywind Tampen (Equinor, 2019) EAs reached similar conclusions, namely that marine mammals will see their habitats enhanced by the increased levels of the fish population due to the FOWT sites having artificial reef effects.

Recent and ongoing research studies have conflicting findings. The Central California and Hawaii Environmental Sensitivity survey (Morandi et al., 2018) found that there likely would be a disturbance to marine mammal habitats, namely in the form of physical barriers in migration paths created by the platform, cables, and mooring lines in the water. The survey also observed that indirect entanglement risk inherently makes the vicinity more dangerous to animals living nearby and stressed that it should be considered to constitute a risk of habitat displacement.

Alterations of physical processes, such as changes in hydrodynamics (i.e., the movement patterns of water, such as currents), can result in changes in habitat suitability and indirect effects on species. Horwath et al. (2020) performed a study on environmental effects from different fixed and floating offshore wind turbine foundations. According to this study, wake effects, which include hydrodynamic changes, for example, increased concentration of prey in wakes and changes to larval recruitment dynamics, would be similar across most foundation types.

Other recent and ongoing research studies support the findings of the existing UK FOWTs EAs. The first is the scaled FOWT in the Gulf of Maine, which found that fish treated the floating mooring lines and cables as an artificial reef (Brady, 2015), enhancing the overall environment for marine mammals, as well. Another study comparing the environmental impacts of offshore wind turbines with different types of foundations, indicates that artificial reef effects exist for both oil and gas rigs (Horwath et al., 2020). The study also affirms previously noted findings that those artificial reef effects are higher for FOWTs than for other types of turbines (Horwath et al., 2020).

Based on available research, risks of habitat displacement are minimal, with some potential for net benefits. The minimal risks may be mitigated by:

- Taking steps to prevent indirect entanglement of marine mammals in mooring lines and cables
- Siting WEAs out of migratory paths

5.4 ENVIRONMENTAL ASSESSMENT FINDINGS

ABSG reviewed environmental assessments from FOWT projects in the UK and Norway and research done in the U.S. OCS evaluating potential environmental impacts of FOWTs to determine the environmental feasibility of establishing FOWTs on the U.S. OCS. ABSG identified three broad categories of potential environmental issues in its review of assessments and research:

1. Loss of access to fishing grounds, negatively impacting both displaced fishers and the areas to which those fishers are displaced
2. Shipping/Navigational hazards, including the need for shipping routes to be altered and risk of collision/allision
3. Impacts of the FOWTs on pelagic life, namely entanglement, habitat displacement, spill risks, and noise impacts

Displacement impacts on fishing and shipping routes, research indicates, are best mitigated by siting WEAs outside of heavily used fishing grounds and shipping routes. The UK FOWT EAs employed landings and AIS data to identify where within the potential FOWT sites fishing and shipping routes were heaviest, and deliberately sited FOWT away from those areas. BOEM should collaborate with wind farm developers, NOAA, state fisheries, and the fishing industry to research wind farm designs, mooring, and cable technology, and fishing methods to minimize impacts within wind farms.

Threats to pelagic life consist primarily of the entanglement of marine mammals in derelict fishing gear that has become ensnared in mooring lines and cables, and spillage, noise, and displacement impacts for marine mammals and fish. The impacts vary in severity and can be mitigated by conducting regular maintenance of the turbines, mooring lines, and cables, and employing maritime and navigational best practices. Table 26 summarizes the key issues and potential mitigation measures compiled from the review of environmental assessments and available research:

Table 26 Issues and Mitigation Summary

Issues	Potential Mitigation Measures
Fishing Grounds Exclusion	Site WEAs outside of heavily used fishing grounds Research FOWT design and mooring/cable technology Research fishing methods
Shipping Disruption	Site WEAs outside of heavily trafficked shipping routes

Issues	Potential Mitigation Measures
Vessel Collision/Allison Risk	Provide ample information to local fisheries about the location and operations of the FOWT
	Regularly inspect and provide maintenance to FOWT moorings and cables
	Employ live AIS traffic monitoring from an onshore station, with procedure to be followed should a ship be on a collision course
	Employ AIS on FOWT and work vessels
	Maintain operational safety zones
	Employ appropriate markings/lighting
Marine Mammal Entanglement	Ensure mooring lines and cables are taut and regularly maintained
	Ensure timely removal of derelict fishing gear that becomes entangled
Chemicals and Liquids Spills	Build using hurricane-resistant materials
	Build in areas less prone to hurricanes, earthquakes, and other natural disasters
	Equip maintenance and other work vessels with oil spill kits
	Employ maritime best practices and navigational aids
Marine Mammals and Fish Noise Impacts	No mitigation necessary
Marine Mammals and Fish Habitat Displacement	Build outside of migratory paths
	Potential net benefits for marine mammals and fish due to artificial reef effect

6 ECONOMIC ASSESSMENT

ABSG reviewed assessments on the economic feasibility of FOWT sites in areas of interest in the U.S. Outer Continental Shelf (OCS):

- California
- Oregon
- Hawaii
- Gulf of Maine
- Atlantic Coast

The economic feasibility of FOWTs in these areas is assessed based on the following factors:

- Levels of wind resources in terms of wind speeds in proposed and potential areas
- Projected technological advancements in the FOWT industry
- Availability of local infrastructure for the fabrication & installation of FOWTs, as well as for grid interconnection
- Local regulatory conditions

Levels of wind resources and projected technological advancement determine the economic feasibility of FOWTs in areas of interest by determining the extent to which FOWT sites can harness economies of scale, wherein per-unit costs are lowered by greater production capacity. Higher levels of wind resources enable a greater harnessing of economies of scale by enabling more wind power to be converted into energy by a FOWT site over the same period of time for the same cost. Technological advancement affects economic feasibility similar to wind, as more advanced technology better enables FOWTs to harness economies of scale and provide a lower per-unit cost of energy. Technological advancements are projected by reviewed research to enable the construction of larger turbines and stronger foundation, which will allow FOWTs to convert wind power into wind energy more efficiently at any wind speed.

Local infrastructure affects the economic feasibility of FOWTs by allowing for lower production costs if:

- Facilities presently capable or capable with minor upgrades/enhancements of fabricating and installing FOWTs are available
- Grid connections are available for FOWTs

Infrastructure must be available to fabricate platforms and turbines, tow them to the open ocean, and install them. FOWTs require a port to be available from which to stage construction of platforms and to conduct routine maintenance. Ports also must have the navigational capacity to receive imported turbines, as the turbines will likely be imported from other countries in the initial stages of a U.S. FOWT industry (Musial et al., 2016). Ideally, FOWT sites would be located on the OCS with ready access to ports able to handle their requirements. If local ports are incapable of handling the fabrication and installation of FOWT platforms without considerable upgrades, then the nearby sites are considerably less economically feasible. The availability of current local infrastructure is assessed for each of the sites of interest.

Lastly, the effects of state regulations on the feasibility of a FOWT site in the areas of interest will be assessed. ABSG's assessment utilizes the following criteria in evaluating the proactivity of state governments and thus the overall favorability of regulatory environments. The favorability of the environment is evaluated based on whether the State:

- Ensures stability in their regulatory regimes
- Is prepared to offer long term contracts to FOWT developers
- Has set renewable energy goals for the future, which FOWTs could contribute to reaching
- Currently has any ongoing FOWT-related activities in state waters
- Entitles utilities to entitled to a full-cost recovery

Regulatory environments are also judged by the degree to which stakeholder barriers pose a challenge. Many entities hold interest in the U.S. maritime domain, ranging from commercial fisheries to the Department of Defense. FOWT sites are considerably less feasible if stakeholders prove difficult to accommodate. As such, the regulatory assessment considers the depth and strength of stakeholder objections in each of the four areas of interest.

6.1 WIND RESOURCES

6.1.1 Overview

Wind resources play a crucial role in determining the economic feasibility of a wind turbine, as the capacity of wind turbines to generate power comes directly from the levels of wind in the vicinity. A wind turbine site established in an area with high wind resources will generate more wind energy than one established in an area with low wind resources, while the costs of establishing and maintaining the turbines are comparable. As such, the average cost per megawatt-hour produced will be lower, all else equal, in the high-wind speed site than the low-wind speed sites. Figure 77 shows the relationship between power generated and wind speed on the turbines for the Block Island Wind Farm, the first wind farm in the U.S. As is readily apparent, the megawatt-hours produced increase as windspeeds. Wind speeds from 11 to 24 meters per second allow for maximum production of wind power. Higher wind speeds tend to overwhelm the turbine and are relatively rare.

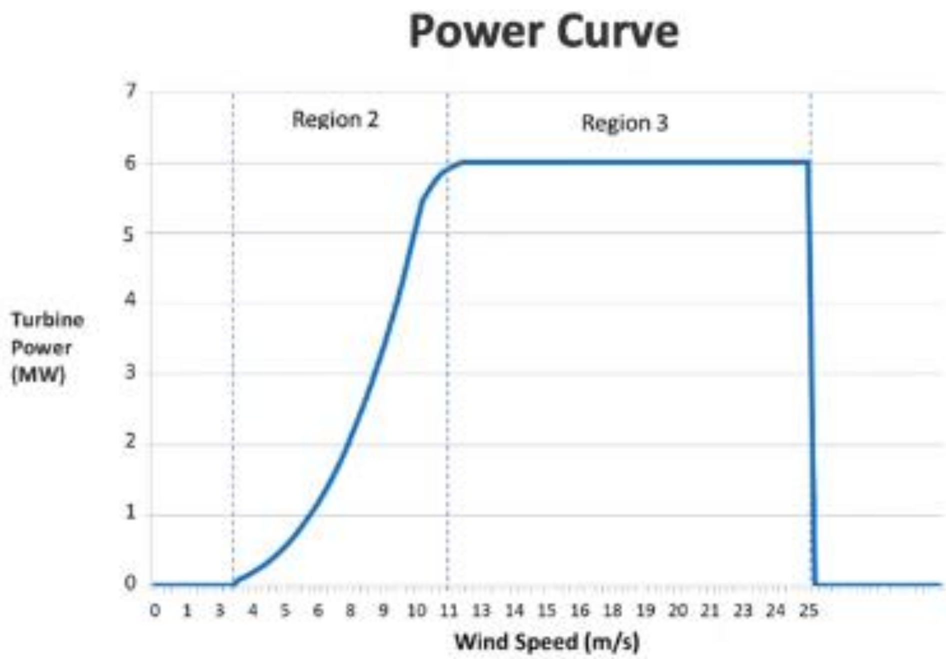


Figure 77 Wind Power Curve (Musial, 2020)

Wind resources tend to be higher offshore than near-shore, meaning that FOWTs have the potential to generate considerably more wind power than the fixed-bottom turbines near shore. Greater amounts of energy harnessed due to greater wind resources will ultimately mean a lower per-unit cost of energy, provided costs of production and installation do not rise proportionally with enhanced capacity.

6.1.2 Areas of Interest

The U.S. OCS off the coasts of California, Oregon, Hawaii, and in the Gulf of Maine are of particular interest to BOEM for potential WEAs. Three call areas for FOWT projects exist already in California, while a fourth exists with two subareas, in Hawaii. The following sections summarize research findings regarding wind resource levels in each of the four areas of interest, drawing from NREL research assessments proposed leases.

6.1.2.1 California

Up to 96% of offshore wind resources in California are in water depths above 60 meters (Musial et al., 2016). Consequently, FOWTs in California have the potential to harness enormous amounts of wind energy in the state. NREL identified potential offshore WEAs in California in a 2016 study, shown in Figure 78. The sites were selected based on six criteria (Musial et al., 2016):

- Annual average wind speed greater than 7 meters per second
- Water depths < 1,000 meters
- Lowest level of conflicts with other offshore utilizations

- Access to transmission on land
- Suitable ports for installation
- Distance from shore

Six locations met the criteria and were deemed suitable for FOWT sites. Of the six, two overlap with existing BOEM Call areas. These are number five, approximately overlapping with the Humboldt Bay Call area, and number three, approximately overlapping with the Morro Bay and Diablo Canyon Call areas. Number five site has an average annual wind speed of 9.73 meters per second, the highest of the six sites examined (Musial et al., 2016).

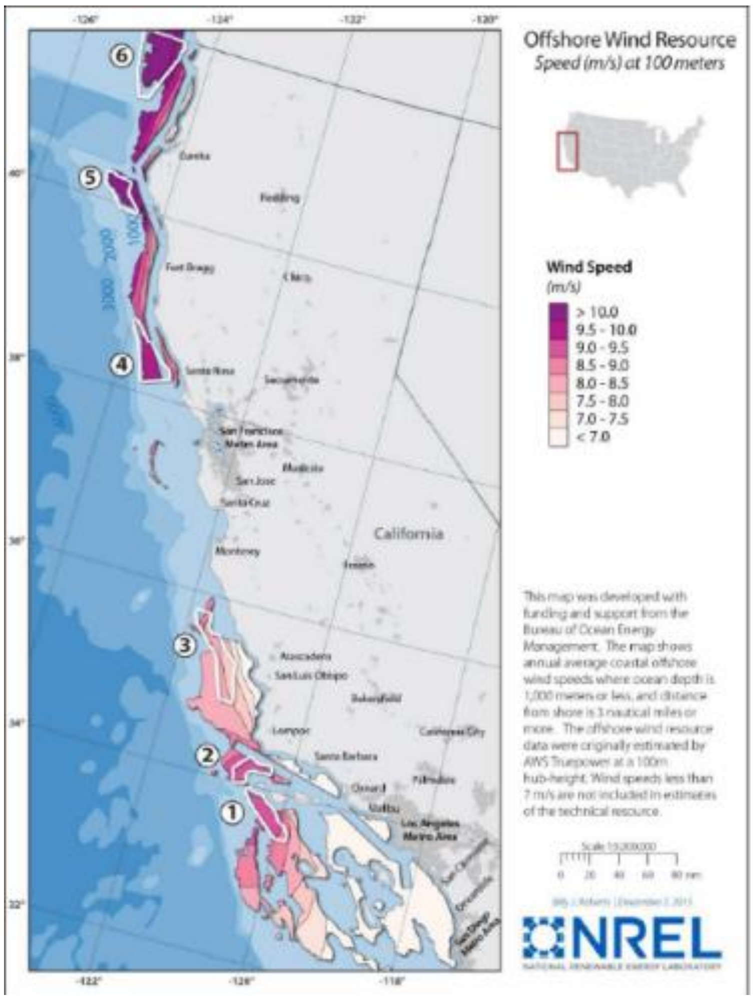


Figure 78 Offshore Windspeeds and Sites in the California OCS (Musial et al., 2016)

6.1.2.2 Oregon

With the small-scale WindFloat Pacific project abandoned, NREL was interested in determining whether larger-scale projects would be feasible off the Oregon coast. NREL conducted a feasibility assessment of potential WEAs in Oregon in 2019, similar to the one conducted for California in 2016 (Musial et al., 2019). The five potential WEAs, geographically dispersed from north to south, were chosen based on the following criteria:

- Continuous clusters within BOEM lease block grid
- Enough space to accommodate a FOWT with a capacity of 1,000 MW
- Avoidance of existing subsea communication and data cables
- Overlap between one of the study sites and the canceled WindFloat Pacific Project

The assessment evaluated wind resource levels in the chosen areas off the coast of Oregon. Figure 79 (Musial et al., 2019) shows the study's findings on wind resources, with a windspeed map of the Oregon OCS overlapped with the five examined potential FOWT sites. Site four overlaps with the abandoned WindFloat Pacific project, off Coos Bay.

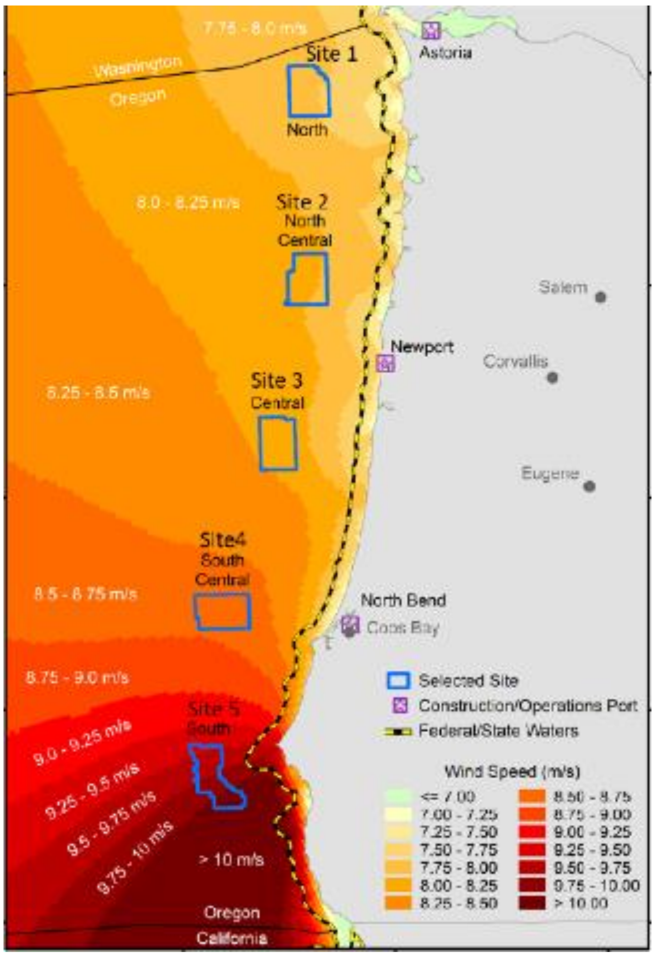


Figure 79 Windspeeds and Sites in the Oregon OCS (Musial et al., 2019)

A strong north-south pattern exists for windspeeds off the coast of Oregon. Wind speeds steadily increase further down the coast. The two Oregon ports meeting depth and clearance requirements, as discussed in the earlier fabrication section, are Astoria and Coos Bay. Astoria is at the far north of the state, with the lowest wind speeds. Coos Bay is toward the south, with greater wind resources. This is one of the key reasons why the now-abandoned WindFloat Pacific project was initially planned for that location. However, any of the sites have sufficient windspeed to accommodate a full-scale Floating Offshore Wind Turbine site.

6.1.2.3 Hawaii

The third area of interest is Hawaii. One BOEM Call area already exists in Hawaii near Oahu, the inhabitants of which some consume some 80% of the state's electricity (Beiter et al., 2017). As of this writing, there exist three proposals for Floating Offshore Wind Turbines: two by Alpha Wind Energy and one by Progression Energy. Both companies, along with NREL, have studied windspeeds off the Hawaiian coast. Figure 80 is an NREL map of wind speeds in the OCS off the coast of the Hawaiian Islands. The island of Oahu, as indicated by the map, generally sees wind speeds of between 7 and 9 meters per second.

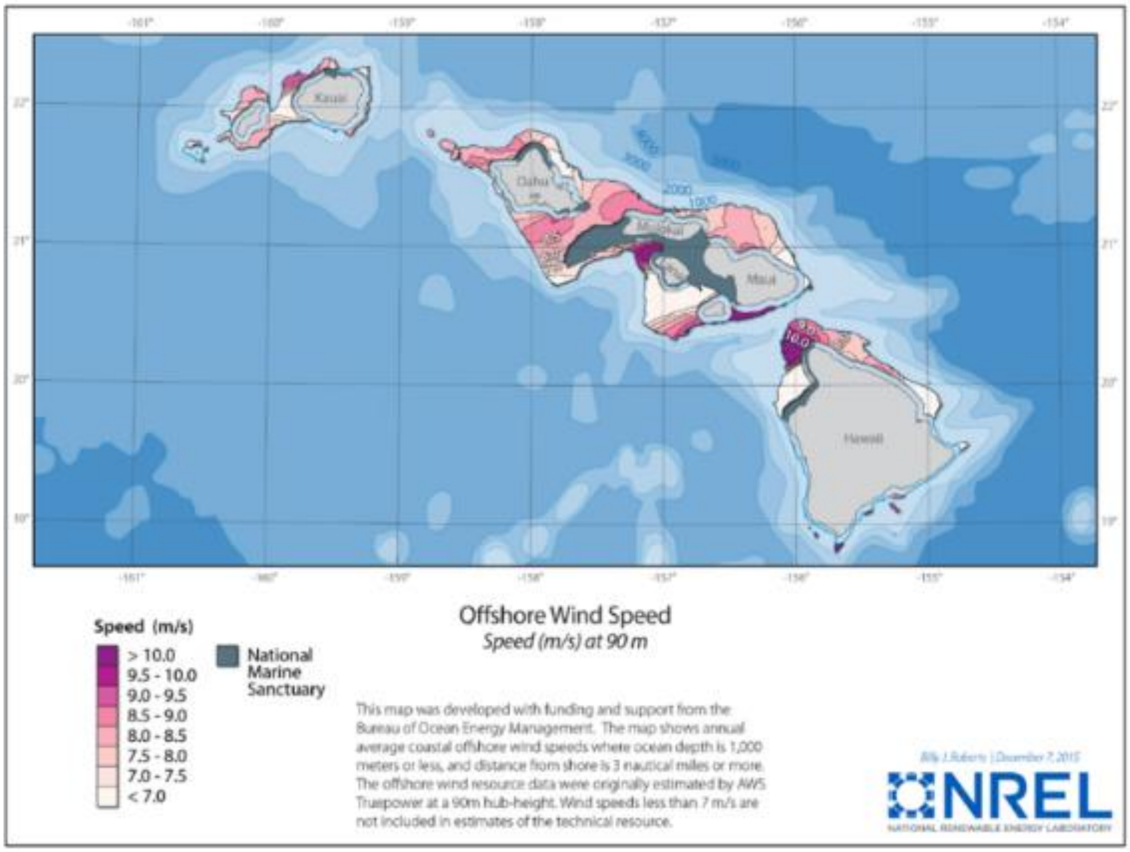


Figure 80 Offshore Windspeeds in the Hawaii OCS (Jimenez, Keyser, and Tegen, 2016)

The firms themselves had similar findings as the NREL: that wind speeds off Oahu fall between 7 and 9 m/s and, therefore, sufficient for a WEA. The figures below show wind speeds off the coast of Oahu as examined by the two firms with lease applications:

Figure 81 Offshore Windspeeds in Southern and Eastern Oahu (Alpha Wind Energy-South Oahu Offshore Lease Application, 2015, pg. 10)

Figure 82 Offshore Windspeeds in Northwest Oahu (Alpha Wind Energy-Northwest Oahu Offshore Lease Application, 2015, pg. 10)

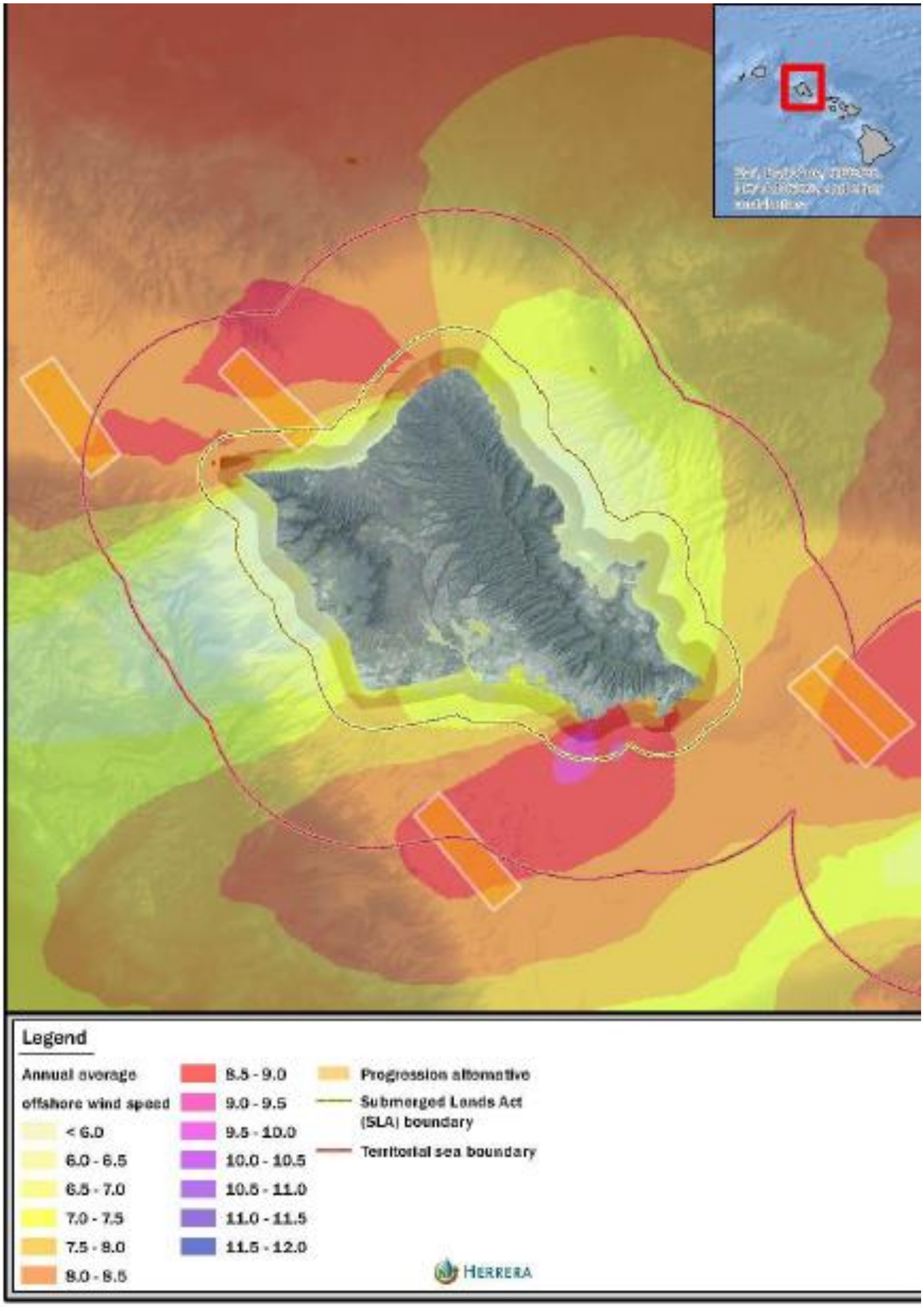


Figure 83 Windspeeds Around Oahu (Progression Energy, 2015, pg. 15)

As the graphics show, the Oahu OCS has high wind speeds, generally falling between 7 and 9 m/s and hovering around 8 m/s on average in the specific potential WEAs. All assessed these wind speeds to be sufficient for large-scale FOWT sites.

6.1.2.4 Gulf of Maine

NREL examined the cost of Floating Offshore Wind Energy in 2020, focusing in particular on the pilot project Maine Aqua Ventus in the Gulf of Maine (Musial, Beiter, and Nunemaker, 2020). The study found that up to 90% of Maine's wind resources exceed 9 meters per second (Musial, Beiter, and Nunemaker, 2020), allowing for great potential for wind energy harnessed. Figure 84 displays a geospatial map of windspeeds across the Atlantic coast and in the Gulf of Maine:

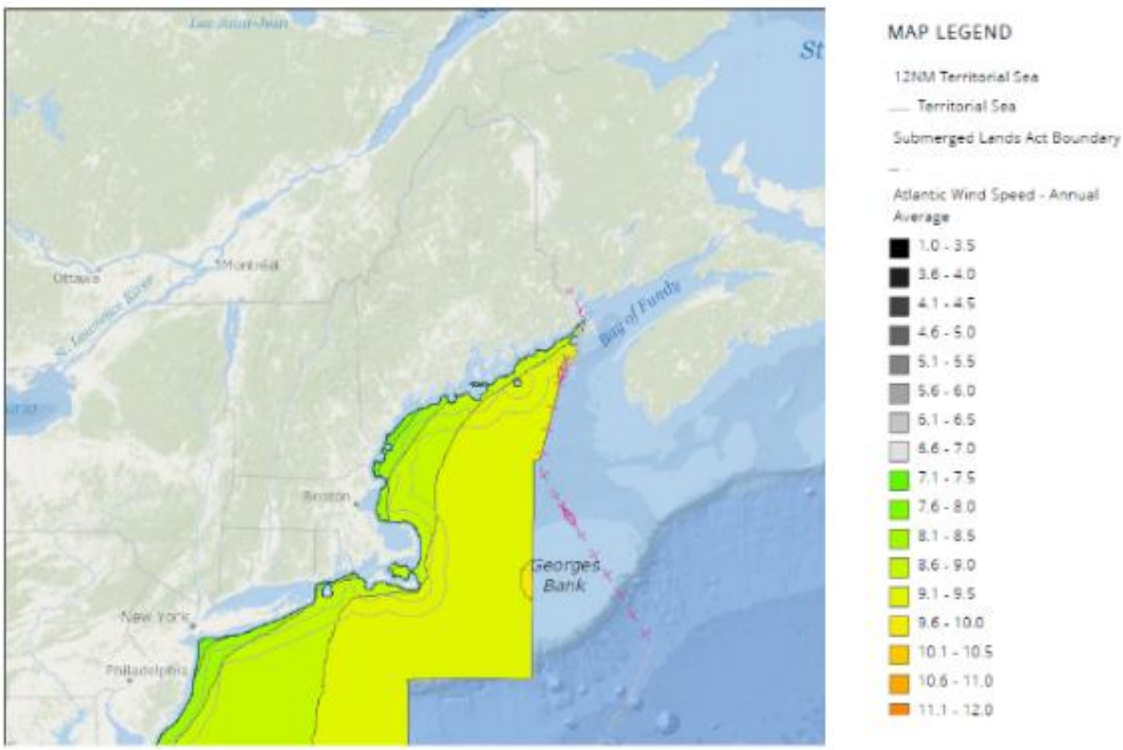


Figure 84 Offshore Windspeeds in the Gulf of Maine (MarineCadastre.gov)

As the figure shows, the Gulf of Maine has greater levels of wind resources than the rest of the Atlantic coast. The wind resources of the Gulf of Maine could potentially produce some 411 terawatt-hours/year (Musial, Beiter, and Nunemaker, 2020), while the state's overall consumption is some 11.2 terawatt-hours/year. Existing wind resources are likely sufficient for the establishment of a WEA to be viable, even if only a fraction of the resources can be harnessed.

6.1.2.5 Atlantic Coast

Musial et al. (2016) presented the wind resource assessment for a distance to shore up to 200 nm. The gross and technical potential resource was calculated using wind speed at a turbine hub height of 100 meters. Water depths more than 60 meters are assumed to require floating platform technology.

State-by-state comparisons were made to determine geographically how the resource is distributed among the 29 offshore states examined. Figure 85 shows this state-by-state comparison for two water depth classes: shallower than 60 meters, and deeper than 60 meters. From this Figure, it can be seen that the Atlantic coast states, including Massachusetts, North Carolina, South Carolina, New York, New Jersey, Virginia, Georgia, Maryland, and Rhode Island, have abundant wind energy resources at water depths larger than 60 meters. The best resource, based on quality and quantity, was found to be in northeast states such as Maine, Massachusetts, Rhode Island, New York, and New Jersey. Massachusetts has the highest offshore wind resource potential.

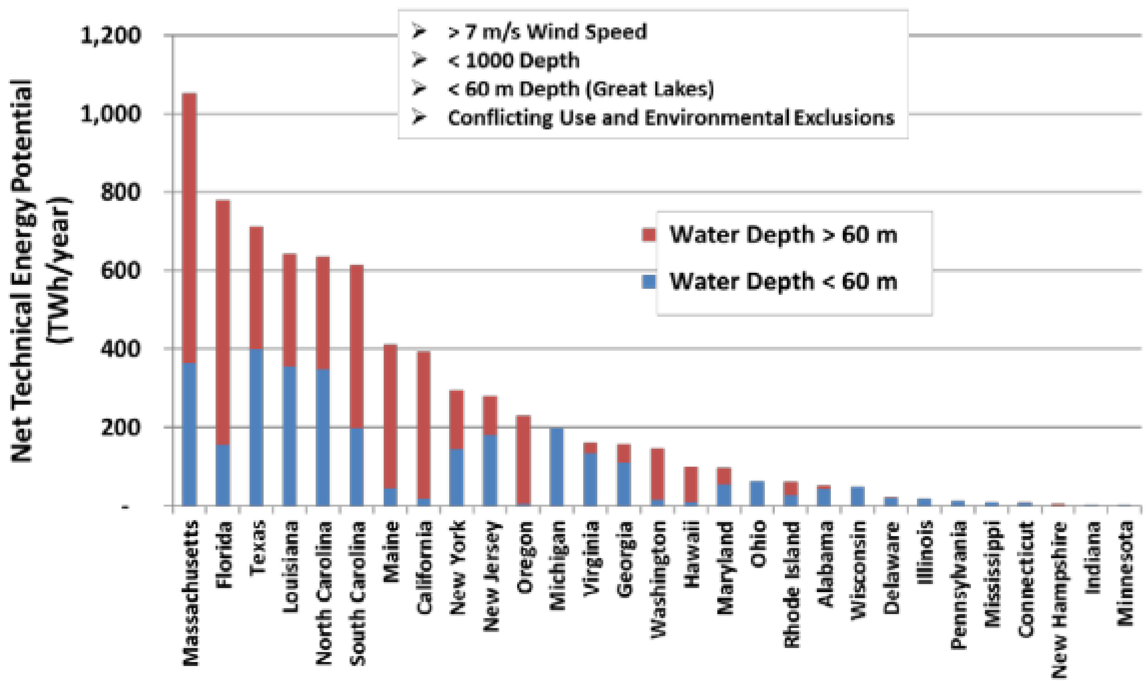


Figure 85 Offshore wind net technical energy potential by state for depths of more than and less than 60 meters (Musial et al., 2016)

6.2 TECHNOLOGY

6.2.1 Overview

ASBG reviewed assessments analyzing the relationship between future technological advancement and the economic feasibility of FOWTs. These assessments analyzed the relationship by modeling the impact future technological advances are likely to have on the cost per megawatt-hour produced (Beiter et al., 2017), termed the Levelized Cost of Energy (LCOE). Technological advancements in the floating wind industry are expected, per assessments reviewed by ABSG, to increase the capacities of the turbines. This will enable them to harness economies of scale by generating more wind energy for the same cost and reducing per-unit prices.

NREL studies found that technological advancements in the FOWT industry overall will likely expand the capacity of wind turbines through larger rotors, more efficient nacelles, and taller towers (Musial et al., 2019). Larger rotors will accommodate larger blades, which in turn will enable a broader swath of wind to be captured and converted into energy for the same cost, lowering per-unit prices. Nacelles are being developed to be lighter (Musial, Beiter, and Nunemaker, 2020), more efficient, and require less maintenance. They will be able to convert and transfer raw wind energy faster, resulting in more wind energy for the same overall cost, thus reducing LCOE. Taller towers are being developed, which will allow for more wind energy generation by accommodating larger blades while maintaining sufficient clearance above the water level.

An academic study out of Sweden on FOWT costs found that taller towers will also better take advantage of the wind shear effect (Heidari, 2017), in which higher altitudes of the same general area have drastically higher windspeeds. The greater level of wind energy produced for the same or similar costs will enable a reduction in the price per megawatt-hour of electricity. The same study found that existing technologies already enable the substructures/foundations of FOWTs to be considerably cheaper than those of fixed-bottom turbines. In particular, installation costs for FOWTs are lower than those for traditional fixed-bottom platforms because fixed-bottom turbines must be installed at sea. Any of the three types of FOWT foundations can be assembled on land and towed offshore (Heidari, 2017). This leads to the vessels required to install a floating foundation, which is also considerably cheaper than those required to install a fixed-bottom foundation.

As MW capacity increases due to technological advances in turbines, the LCOEs associated with each of the three types of substructures and foundations are expected to decrease and converge. Figure 86 shows the findings from the Swedish study. Depicted is the projected fall in LCOE, given the increased capacity of the FOWT. Note that the LCOEs associated with the different types of substructures/foundations converge; as capacity increases, the differences between the substructures/foundations become smaller, giving developers more flexibility to decide which ones to use. Table 27 shows the projected amount of LCOE decrease between the platforms as technology allows FOWT capacity to increase from 3 MW to 10 MW. Not only do unit costs fall for FOWTs associated with each substructure/foundation, but the difference between the costliest and least costly falls, as well.

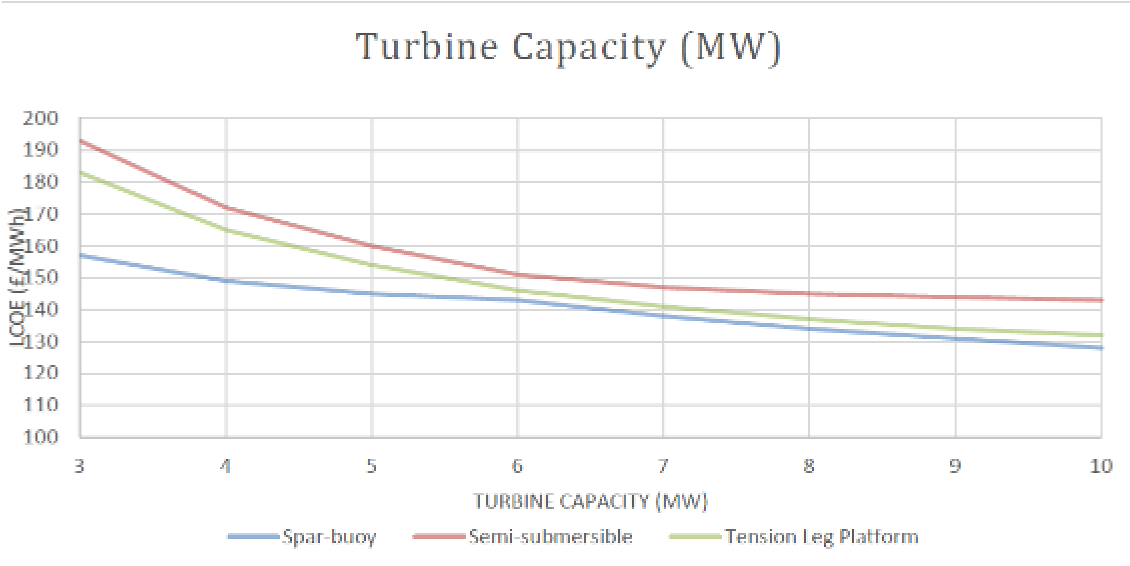


Figure 86 Modeled Turbine Capacity and LCOE by Foundation Type (Heidari, 2017, pg. 42)

Table 27 Modeled Differences in LCOE from 3 MW to 10 MW by Foundation Type

Platform	3 Mw LCOE	10 Mw LCOE	Difference
Semi-Submersible	~190	~145	~45, or 24% decrease
Tension Leg Platform	~180	~140	~40, or 22% decrease
Spar-Buoy	~160	~140	~20, or 13% decrease

6.2.2 Areas of Interest

6.2.2.1 California & Oregon

Over time, increased turbine capacity is expected to substantially reduce costs on the coasts of California and Oregon. Figure 87 shows NREL's projected fall in the LCOE from 2015-2027 due to evolving technologies. LCOE is projected to steadily decrease over the course of the twelve analyzed years.

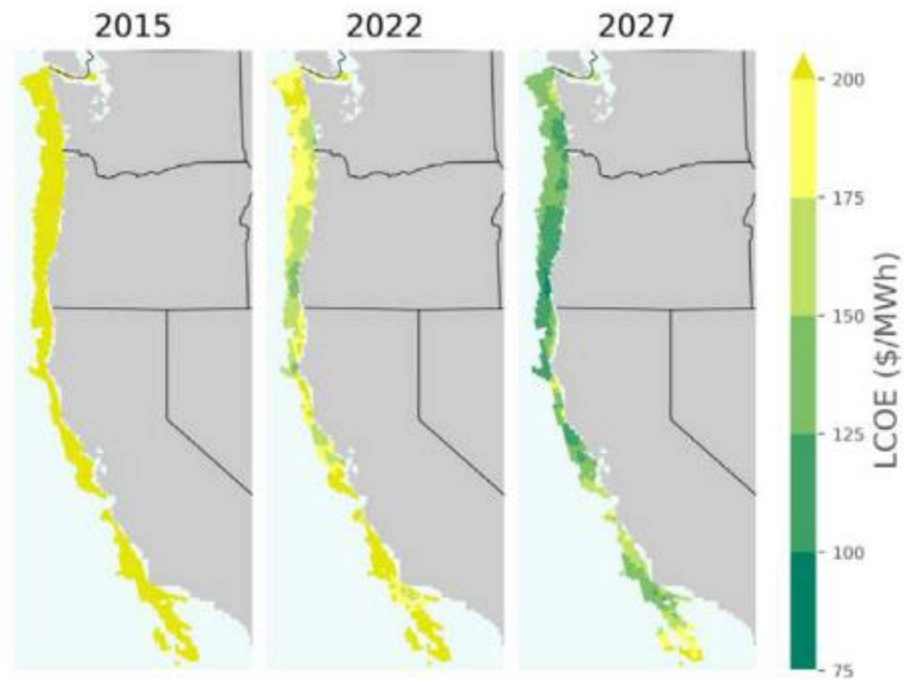


Figure 87 Falling LCOE on the Pacific Coast (Beiter et al., 2017, pg. 37)

California LCOE is expected to decrease significantly due to technological advancement in turbines. The turbine capacity is expected to reach 12-15 MW operating capacity by the middle of the 2020s (Collier, 2017). Ultimately, California FOWTs are expected to be capable of harnessing over 70% of the potential wind energy available (Collins & Daoud, 2019).

The NREL feasibility study of California expected that rotor and hub sizes to expand considerably, and the assumptions it made about technological advancement are shown in Table 28. The study found that the expected LCOE near the Humboldt Bay call area is projected to fall from $188/MWh in 2015 to $100/MWh in 2030 (Musial et al., 2016).

Table 28 California Feasibility Study Technological Assumptions (Musial et al., 2016, pg. viii)

	2015 Technology	2022 Technology	2027 Technology
Turbine Rated Power (MW)	6	8	10
Turbine Rotor Diameter (m)	155	180	205
Turbine Hub Height (m)	100	112	125
Turbine Specific Power (W/m^2)	318	314	303
Substructure Technology	Semisubmersible	Semisubmersible	Semisubmersible

The NREL feasibility assessment for Oregon in 2019 also yielded findings along these lines, even more optimistic than California because of "new industry data and modeling assumptions" (Musial et al., 2019). All sites, including site 1 near Astoria and site 4 near Coos Bay (Overlapping where WindFloat Pacific was originally planned), see marked decreases in LCOE over the course of the next decade. Figure 88 shows the projected fall in LCOE for each of the examined sites.

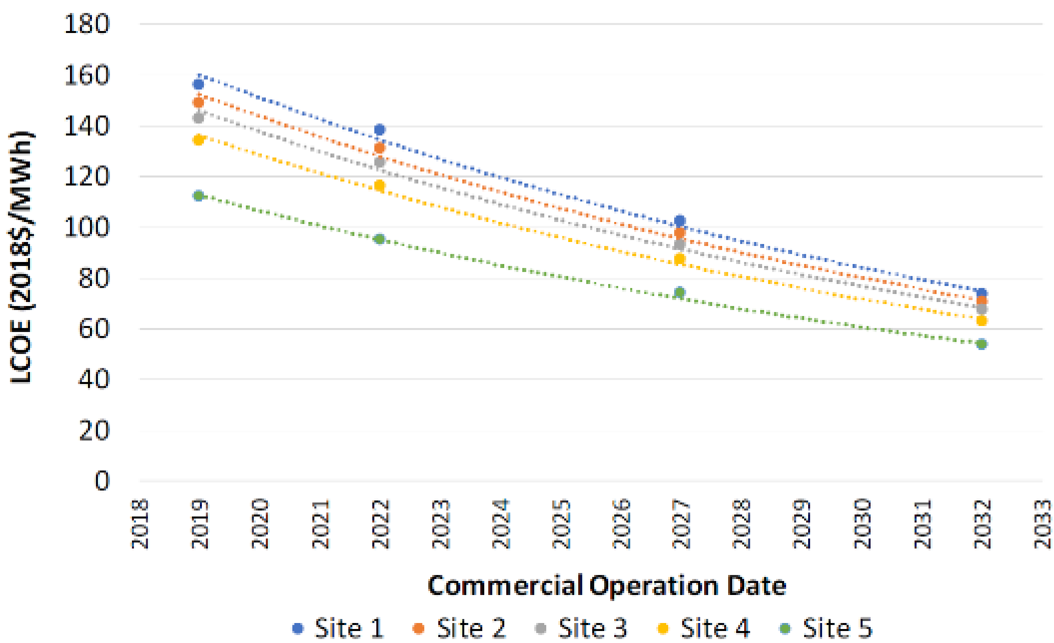


Figure 88 Projected LCOE Decrease at Examined Oregon Sites (Musial et al., 2019, pg. ix)

6.2.2.2 Hawaii

NREL projects that technology will decrease costs in Hawaii over the coming years (Beiter et al., 2017). In particular, costs are projected to decrease from over $200/MWh to mainly under $125/MWh, and possibly below $100/MWh, as shown in Figure 89.

Figure 89 Falling LCOE in Hawaii (Beiter et al., 2017, pg. 53)

Progression Hawaii. (Progression, 2015), and Alpha Wind Energy (Alpha Wind Energy, 2015) each propose to implement turbine sites with total capacities of 400 MW. Alpha Wind stated in its lease application that it found FOWT technology has advanced to the point currently where the project is "viable" (Alpha Wind Energy, 2015) in Hawaii. The Progression lease application finds that the expected LCOE of the project once established would be comparable to that of solar energy, and that the project could meet up to 25% of Oahu's electricity need (Progression, 2015).

6.2.2.3 Gulf of Maine

In the Gulf of Maine, unit costs of energy production from FOWTs are also expected to decrease due to technological advancement, as seen in Figure 90.

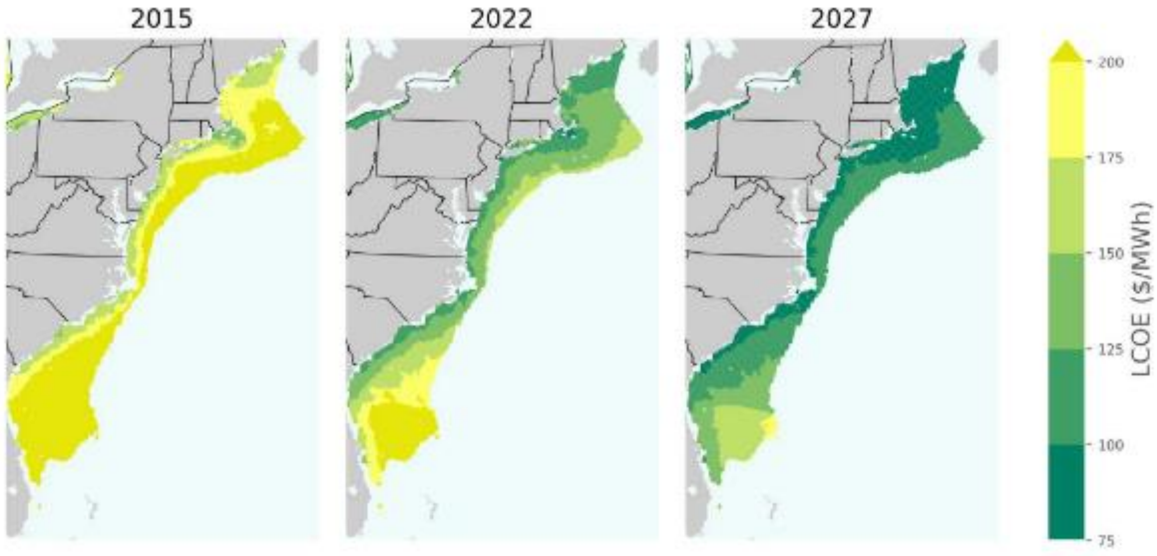


Figure 90 Falling LCOE on the Atlantic Coast (Beiter et al., 2017, pg. 31)

Studies on likely FOWT cost reductions have been performed on the Aqua Ventus project in the Gulf of Maine. Aqua Ventus researchers and the University of Maine, using assumptions based on available technology, predict significant cost savings from increased turbine sizes in the coming decades. Ultimately, the capacity of turbines is expected to grow from 6 MW in 2019 to 15 MW in 2032 (Musial, Beiter, and Nunemaker, 2020), summarized in Table 29. These capacities will come from developments in rotor sizes and tower heights. The increased sizes of the wind turbines are projected to decrease the LCOE of a full-scale project in the Gulf of Maine from $107/MWh in 2019 to $57/MWh in 2032 (Musial, Beiter, and Nunemaker, 2020). These projections have carried weight with actual developers: the University of Maine and Aqua Ventus are planning to deploy a full-scale, 12 MW turbine within the next few years (University of Maine, 2020), and GE announced recently that its 12 MW turbine is expected to be commercially available by 2022 (Musial, Beiter, and Nunemaker, 2020).

Table 29 Aqua Ventus Technological Projections (Musial, Beiter, and Nunemaker, 2020, pg. 16)

Technology	Commercial Operation Dates			
	2019	2022	2027	2032
Turbine Rated Power (MW)	6	10	12	15
Turbine Rotor Diameter (m)	155	178	222	248
Turbine Hub Height (m)	100	114	136	149
Turbine Specific Power[12] (W/m²)	318	410	310	311
Wind Plant Size (MW)	600	600	600	600
Capital Recovery Period (years)	30	30	30	30
Substructure	Aqua Ventus Semisubmersible	Aqua Ventus Semisubmersible	Aqua Ventus Semisubmersible	Aqua Ventus Semisubmersible

6.2.2.4 Atlantic Coast

The study by Beiter et al. (2017) offers insights into the available U.S. offshore wind resource by region at different levels of LCOE and an assessment of the present and future economic potential of that resource capacity up to 2030. In the Atlantic coast, unit costs of energy production from FOWTs are also expected to decrease due to technological advancement, as seen in Figure 90.

6.3 INFRASTRUCTURE

6.3.1 Fabrication and Installation

The ability of the local infrastructure to facilitate the fabrication and installation of the FOWT components are integral to the success of FOWTs in the U.S. Outer Continental Shelf. Because turbines are at least initially likely to be imported from abroad (Musial et al., 2016), local ports must have the capacity to:

- Fabricate offshore platforms
- Stage turbines in port
- Install FOWTs
- Maintain installed FOWTs

Fabricating the offshore platforms will require rail access (Porter and Phillips, 2016), a workforce capable of constructing them, and facilities of sufficient size to construct them. Semi-Submersible platforms and Tension Leg platforms are expected to be staged in port, with the turbines placed on top of the platforms and towed to the site. The best assemblage strategy for Spar-Buoy platforms is still in development. Prototypes have been assembled in deep water locations. Table 30 identifies a strategy for installing FOWTs with each of the different types of platforms.

Table 30 FOWT Foundation Installation Concepts (Porter and Phillips, 2016)

Device	Material	Installation Concept	Primary Installation Vessels	Other
Semi-Sub	Steel	Assembled in port & towed to site	Anchor Handling Tug, support tugs	May be constructed in dry dock
TLP	Steel	Assembled in port & towed to site	Multiple Ocean Tugs	
Spar	Steel	In development. Prototype assembled in protected deep water location	Anchor Handling Tug, Crane Barge	May be towed horizontally to assembly site.

A BOEM study on FOWT infrastructure identifies the necessary criteria for FOWT assembly and installation, as shown in Table 31.

Table 31 Primary Criteria for an Assembly Port (Porter and Phillips, 2016)

Criteria	OFW			Comment
	Semi-Sub	Spar	TLP	
Throughput Capacity	30+	30+	30+	Assumed commercial-scale
Primary Criteria				
Navigation Channel Width	>=~330-440 ft.	~200-300 ft.	>~300-440 ft.	If berthed quayside, device must have 100 ft. minimum offset from navigation channel.
Navigation Channel Depth	32-39 ft. (conceptual)	~20-30 ft. if assembled at sea (depending on vessel). ~ 300 ft. if assembled in protected waters.	32-39 ft.	
Air Draft	Unlimited	Unlimited	Unlimited	
Area	10-15 acre minimum 50-100 acre ideal	10-15 acre minimum 50-100 acre ideal	10-15 acre minimum 50-100 acre ideal	Assembly only. Depends on size of windfarm.

Ports, where the FOWT components will be staged, require sufficient channel width and depth to accommodate the FOWTs, along with (Sathe et al., 2020):

- Ample room to lay down turbines
- High vertical clearance (up to 250 meters)
- Sufficient quayside length, weight-bearing capacity, and depth to support platform assembly
- Sufficient cranage
- Dry docks are also preferred (Porter and Phillips, 2016)

Sufficient navigation channels and berthing areas are also required for vessels to tow the staged turbines out to sea. The ports must be deep and wide enough to allow for tugboats with the FOWTs attached to them. They must also be sufficiently deep and wide to allow maintenance vessels to travel in and out and located reasonably close to the installation site.

6.3.1.1 Areas of Interest

The following section examines assessments of local infrastructure and upgrades likely to be needed in the areas of interest. In particular, ABSG reviewed assessments of infrastructure near the Humboldt Bay, Morro Bay, and Diablo Canyon call areas off of the coast of California, the Astoria, and Coos Bay ports in Oregon, infrastructure near the Oahu call area in Hawaii, the Gulf of Maine, and ports for assembly in Atlantic Coast. Based on the available technology and infrastructure, along with demand for renewable energy from States on the east and west coasts, the development of FOWTs in the next 5 to 10 years is certainly feasible.

6.3.1.1.1 California

The northernmost California call area, Humboldt Bay, has the available local infrastructure but faces some potential challenges. Necessary for assembly, the only deepwater port in this call area is Humboldt Bay itself (Sathe et al., 2020), though smaller ports such as Fields Landing are available nearby for O&M activities. Humboldt Bay is, in some respects, a strong candidate for an assembly/fabrication port. The area surrounding Humboldt Bay has vast expanses of unused land that could be used for fabrication and laydown assembly of turbines, for instance (Collier, 2017). The port has the necessary vertical clearance heights, and necessary channel width and depth for towing platforms out to sea. However, Humboldt Bay lacks railway and highway access (Collier, 2017), which would need to be made more robust to support a full-scale FOWT project. The 2016 BOEM assessment of local infrastructure on the West Coast for offshore wind turbines also found that Humboldt Bay "would likely require quayside upgrades to support staging and transport of materials" (Porter and Phillips, 2016). Humboldt Bay also faces a seasonality problem; due to large deposits of sediment from the Eel River each year into the Bay, O&M activities are expected to be severely limited for months at a time (Sathe et al., 2020). This would be expected to raise O&M costs considerably.

The Morro Bay and Diablo Canyon call areas in central California have some strengths and weaknesses compared to Humboldt Bay in terms of available local infrastructure. The NREL assessment examining potential sites in California found that a central CA FOWT site would likely rely on Port Hueneme to be an assembly port (Musial et al., 2016), as Diablo Canyon has no port, and the port of Morro Bay lacks the navigational depth and width to serve as an assembly port (Porter and Phillips, 2016), though it could feasibly serve as an O&M port in the area. Port Hueneme, the port of Morro Bay, and other ports in the region do not see seasonality impacts the way Humboldt Bay does; O&M activities could take place year-round. Port Hueneme was assessed by the BOEM report on available infrastructure to be a strong candidate for an assembly port, with sufficient navigation channel width and depth, along with robust highway/rail access (Porter and Phillips, 2016). Port Hueneme and the central CA call areas also face some challenges Humboldt does not. For instance, Port Hueneme would likely need more upland area to be fully able to accommodate turbines (Porter and Phillips, 2016), and Port Hueneme is heavily used and congested already. The UC Berkeley report found that while owners of Port Hueneme and other big southern California ports were willing to host O&M activities, they are resistant to the idea of their spaces being used for assembly/fabrication (Collier, 2017), and that developers may face challenges in renting the needed space from those ports.

6.3.1.1.2 Oregon

The NREL economic feasibility study analyzing local infrastructure across Oregon found that while several potential service ports are available along the Oregon coast for O&M (Musial et al., 2019), only the ports of Astoria and Coos Bay meet the depth and clearance requirements for staging and installing FOWTs. (Musial et al., 2019). One port, Newport, met the depth requirements but was excluded as a suitable site because of the low clearance level of a nearby bridge.

The 2016 infrastructure assessment examined both Astoria and Coos Bay. Both were found, broadly, to be suitable for the fabrication and assembly of FOWT structures with modest upgrades. (Porter and Phillips, 2016). Astoria would likely require greater terminal acreage and upland area to be feasible, given the space needed to assemble turbines, though its navigation channel width and depth were gauged to be sufficient. Coos Bay "may or may not," per the assessment, be able to facilitate the fabrication of FOWTs due in large part to limited rail and highway connection and a lack of upland area (Porter and Phillips, 2016). The assessment also raised concerns over whether Coos Bay's navigation channel would be wide enough to accommodate the towing-out of staged FOWTs, as the channel width is 300 feet and devices may be greater than 150 feet. Coos Bay was selected for the now-abandoned WindFloat project, due to its history as an industrial port (Banister, 2017). Facilities at Vigor Shipyards in Portland, Oregon, part of the local supply chain, would have contributed to the construction of the project, and may also do so in the future.

6.3.1.1.3 Hawaii

One BOEM Call area exists off the coast of Hawaii with two distinct subareas: one in northern Oahu and one in southern Oahu.. The 2016 infrastructure assessment of Hawaii and the West Coast identifies two Hawaiian ports that could potentially serve as fabrication and assembly ports for a FOWT site: Honolulu and Barber's Point (Porter and Phillips, 2016). The assessment found that the two ports had similar strengths and weaknesses. The primary strength of the two ports is that they have the navigation channel widths and depths necessary to accommodate staging FOWTs and towing them out to sea (Porter and Phillips, 2016). Additionally, Honolulu currently has a dry dock, while Barber's Point has had one in the past and may have "suitable berthing for dry docks" (Porter and Phillips, 2016). However, both ports lack the upland area necessary for fabrication (Porter and Phillips, 2016). Overall, the assessment found Barber's Point to be a more suitable fabrication/assembly port, with stronger quayside capacity and more upland area to be used.

The three proposed leases for the Oahu call area-Alpha Wind Energy in northwestern and southern Oahu and Progression in southern Oahu-also assessed the suitability of local infrastructure for fabrication and installation. The Alpha Wind Energy leases predicted that most components would be produced outside of Hawaii and shipped to the Hawaiian port for assembly, and found that "suitable harbors are available for manufacturing, servicing, and maintenance of the project" (Alpha

Wind Energy, 2015). Progression plans to have its cables make landfall near Barber's Point (Progression, 2015).

6.3.1.1.4 Gulf of Maine

Preliminary research on available infrastructure has been accomplished by the Aqua Ventus test project and abandoned Hywind Maine project. The projects indicate Searsport may be a viable deepwater port to serve as a hub for floating wind. Searsport was projected to be the hub for the ultimately abandoned Hywind Maine project. Hywind Maine was to have two assembly sites (Keiser 2014). One was Sprague Terminal at Mack Point, with an onshore port facility to be used for storage. The other was Penobscot Bay, with an inshore area to be used for assembling the FOWT. Both Mack Point and Penobscot Bay are within the vicinity of Searsport. Hywind Maine was abandoned in 2013, citing "uncertainty of state regulations" (Richardson, 2013), rather than any shortcomings within Searsport.

Mack Point Marine Intermodal Cargo Terminal (World Port Source, 2020), the primary cargo-handling facility at Searsport, has two berths. Both have navigation channels 800 feet wide, with one being 40 feet deep and the other 32 feet deep. Some 70 acres is also available to the port "for development" per the World Port Source (World Port Source 2020), and the Port has rail access via the Canadian Pacific Railway.

As of March 2020, Governor Mills had directed the Maine Department of Transportation and other agencies to assess the feasibility of Searsport as a potential Floating Offshore Wind hub (Bever 2020). Plans have also been renewed to base a full-scale turbine out of Searsport, with several firms looking to construct the full-scale Aqua Ventus project (Bever, 2020). Currently, Aqua Ventus FOWT is to be located at a test site off the coast of Monhegan Island in state waters. It is to be fabricated with locally sourced materials, and regularly maintained from nearby ports (Musial et al., 2020).

6.3.1.1.5 Atlantic Coast

According to The Maritime Executive (2016), for the first operating offshore wind farm in U.S., the Block Island offshore wind farm, four Rhode Island ports – at Block Island, Galilee, Quonset Point, and ProvPort were used to complete construction and staging.

According to Musial et al. (2018), developers and state bodies have started to make investments in port infrastructure to make sure there are sufficient cranes and laydown space required for large-scale commercial projects. Approximately five staging ports will be required to meet the needs for the first 10 GW of offshore wind deployment on the Atlantic Coast alone.

There are few ports along the Atlantic Coast that have made recent infrastructure investments to upgrade and prepare for the first wave of projects as listed below:

- Massachusetts, Port of New Bedford: Vineyard Wind is leasing the New Bedford Commerce Terminal for 18 months as the primary staging and deployment base for its 800-MW project.
- Massachusetts, Brayton Point: Anabaric and Commercial Development Company signed an agreement to invest $650 million into Brayton Point's Commerce Center to create an

offshore wind hub that has a 1.2-GW high-voltage direct-current converter, 400-MW battery storage, and additional wind turbine component laydown space.

- Connecticut, New London: Ørsted, the Connecticut Port Authority, and Gateway will invest $152 million in the State Pier at New London to expand the laydown space, increase its heavy-lift capacity, and add other features necessary for large-scale offshore wind development activities. Ørsted will lease rights to use the pier for 10 years.
- Maryland, Tradepoint Atlantic (Formerly Sparrow Point): In 2017, US Wind and Deepwater Wind agreed to invest $115 million in new manufacturing and port infrastructure.

In June 2020, Nexans, a submarine power cable manufacturer, was contracted to supply SSE Renewables to supply power export cables for Scotland's Seagreen offshore windfarm project. The three 65 kilometers offshore export cables will be manufactured in Nexan's Charleston, SC facility, which was recently expanded to manufacture HV subsea power cables and is currently the only facility with that capability in North America (Nexan, 2020).

New Jersey announced in September 2020 the development of the New Jersey Wind Port, located on the Delaware River in Lower Alloways Creek Township, with an estimated construction cost between $300-400 million. Phase one of the project is scheduled to commence construction in 2021 and be completed in 2023 with a 30-acre marshaling area for component assembly and staging, a 25-acre component manufacturing site, and a dredged channel to the site. Phase two adds 150-acres for marshaling and manufacturing facilities for turbine components (NJ EDA, 2020).

Another offshore wind component manufacturer is locating to New Jersey on the Delaware River. EEW Group, a German manufacturer of steel monopiles and jacket foundations, and Orsted invest $250 million to build a manufacturing facility, to build steel components for offshore wind turbines at the Port of Paulsboro (Hurdle, 2020). EEW will initially build monopiles for Orsted wind farms. The structures will be up to 40 feet in diameter and 400 feet tall, made with a five-inch-thick steel plate, and weighing up to 5 million pounds each (Hurdle, 2020).

Equinor was selected to provide New York State with 2,490 MW of offshore wind power from its Empire Wind 2 and Beacon Wind 1 projects in January 2021. As part of the award by NYSERDA, the South Brooklyn Marine Terminal (SBMT) and the Port of Albany, will be developed into offshore wind working industrial facilities (Equinor, 2021). Equinor will upgrade the SBMT int offshore wind staging and assembling facility and an operations and maintenance (O&M) base both for Equinor and other project developers. At the Port of Albany, Equinor, together with wind industry companies Marmen and Welcon, will develop a manufacturing facility to build offshore wind towers, transition pieces, and other components for Equinor's projects (Equinor, 2021).

6.3.2 Grid Connection

The "transmission bottleneck" (Collier et al., 2019) is one of the most fundamental obstacles to FOWTs in the OCS. Suitable infrastructure may exist to fabricate and install components and wind resources, and technological advancement may produce abundant energy. However, wind power is ultimately only as effective as the capacity of the electric grid to receive it. The four areas of interest, California, Oregon, Hawaii, and the Gulf of Maine, have varying abilities in their grid to absorb FOWT-produced energy, and depending on where sites are ultimately leased, substantial investment in altering electric grids may be necessary.

6.3.2.1 Areas of Interest

6.3.2.1.1 California

Five sites in the California OCS were evaluated by the University of California at Berkeley's Center for Labor Research and Education (Collier et al., 2019) for possible FOWT sites. Three of them lie within California call areas:

- Morro Bay (Call Area)
- Diablo Canyon (Call Area)
- Humboldt Bay (Call Area)
- Cape Mendocino
- Del Norte

Table 32 shows each of the evaluated sites' capacity factor, expected LACE and LCOE, and transmission availability. The capacity factor is the percent of available wind resources able to be harnessed. LCOE, as discussed earlier, is the cost of producing one megawatt-hour. LACE, or Levelized Avoided Cost, is similar to LCOE, except it is a measure of how much money is saved by using Floating Wind energy rather than an alternative source. Transmission availability is the amount of extra capacity in the electric transmission grid to accommodate additional power. Diablo Canyon and Morro Bay, as shown in the table, are similar to the other sites in terms of capacity factor, LACE, or LCOE. The major difference is Morro Bay and Diablo Canyon- are the only sites with transmission availability. Diablo Canyon has a 3,933 MW of capacity in its transmission network that could be filled by energy produced with FOWTs in the area.

Table 32 California Offshore Wind Sites (Collier et al., 2019, pg. 8)

Offshore Wind Resource Zones	Simulated Capacity Factor	Average Avoided Costs 2030 50 LACE, 2 GW scale*	2025-2030 Cost Range LCOE, NREL ATB+E3	Transmission Availability (MW)
Morro Bay	55%	$80/MWh	$62 to $72/MWh	668
Diablo Canyon	46%	$81/MWh	$74 to $88/Gh	3,933
Humboldt Bay	51%	$88/MWh	$66 to $78/MWh	Minimal
Cape Mendocino	53%	$82/MWh	$65 to $76/MWh	Minimal
Del Norte	51%	$83/MWh	$66 to $78/MWh	Minimal

The contrasts between the sites are more distinct when comparing the mega wattage of potential resources, shown in Table 33, and the megawattage available for transmission. Diablo Canyon is the only site with a transmission availability close to its resource potential, due to the presence of the nearby Diablo Canyon Nuclear Power Plant. The power plant is slated to cease operations in 2025, which would allow a FOWT project to connect to the grid in its place. Morro Bay was assessed by the NREL as likely to also connect to the grid transmission at Diablo Canyon (Musial et al., 2016), even though Morro Bay has a shuttered power plant nearby, as well.

Table 33 California Sites Offshore Wind Resource Potential (Collier et al., 2019, pg. 57)

Offshore Wind Resource Zone	Resource Potential Area (Sq. km)	Resource Potential (MW)
Del Norte	2,201	6,604
Cape Mendocino	2,072	6,216
Diablo Canyon	1,441	4,324
Morro Bay	806	2,419
Humboldt Bay	536	1,607
Total	**7,051**	**21,171**

The third Call area in California, near Humboldt Bay, faces severe difficulties with the transmission. Humboldt Bay, per the Berkeley study, has minimal transmission availability (Collier et al., 2019). The Schatz Center performed a cost analysis of establishing a suitable grid connection to Humboldt Bay (Severy et al., 2020). The study analyzed the cost of establishing grid connections for three different FOWT project scales:

1. 48 MW
2. 144 MW
3. 1,836 MW

The study was conducted under the assumption that the floating wind farms and other regional power sources would be operating at peak capacity. Table 34 displays the low and high-end cost estimates of necessary transmission upgrades for each of the three project scales. As is readily apparent, the upgrades needed for a suitable grid connection in the call area near Humboldt Bay would be quite expensive.

Table 34 Humboldt Bay Grid Connection Cost Estimates (Severy et al., 2020)

Scale	Low-End Cost Estimate	High-End Cost Estimate
48 MW	$363 Million	$726 Million
144 MW	$669 Million	$1.34 Billion
1,836 MW	$1.4 Billion	$2.8 Billion

Humboldt Bay's electricity grid is set up to accommodate the relatively light demand the area currently has. The two smaller-scale FOWTs are assumed by the study to connect to the grid at the Humboldt Bay 115 kV substation (Severy et al., 2020), which would require extensive reconductoring and the construction of entirely new transmission lines. The larger scale project would require a 500 kV facility, of which Humboldt Bay has none. A 500 kV line would need to be built to connect to other locations, likely the 500 kV substation at Round Mountain, Vaca Dixon, or via HVDC subsea transmission cable to the San Francisco Bay Area (Severy et al., 2020). The Redwoods Coast Energy Authority, in its nomination letter to BOEM for a lease application (Thurston, 2019), implicitly recognized the difficulty in establishing a full-scale FOWT in Humboldt Bay, proposing instead a 100-150 MW project in the Northern California Call Area.

6.3.2.1.2 Oregon

ABSG reviewed assessments performed by the National Renewable Energy Laboratory (Musial et al., 2019) and PNNL (Douville et al., 2020) on the feasibility of grid interconnection in Oregon. The NREL study was broader in nature, examining the grid interconnection issue in the context of overall feasibility, while the PNNL report focused on maximizing the value of a grid interconnection. Ultimately, the studies found that 2-3 GW of offshore wind energy was feasible and could be accommodated by the coast without significant changes to the Oregon grid, but a larger project would cost significantly more due to necessary upgrades to the transmission grid.

The NREL study was broad, evaluating the overall economic feasibility of five specific Oregon sites, including grid connection. For the grid connection portion of the analysis, the study analyzed a scenario in which 100% of Oregon's energy comes from renewable sources, with 80% from wind power specifically. The assessment found that a FOWT project capacity of approximately 5 GW (Musial et al., 2019) would be needed to meet Oregon's requirements in this scenario. The assessment found that the Oregon transmission grid poses difficulties in establishing a 5 GW FOWT site, because the current electrical grid is assembled such that power flows from the central Willamette valley westward to the coastal communities, as shown in Figure 91. Sites of interest examined by NREL are circled in green. Power from a large FOWT project into the grid, flow directions would need to change considerably, if not reverse completely (Musial et al., 2019). The study found that such an injection could benefit the state grid overall by relieving energy congestion in the eastern part of the state. However, the study did not draw a conclusion regarding how much such a flow reversal would cost, and whether it would be prohibitively expensive.

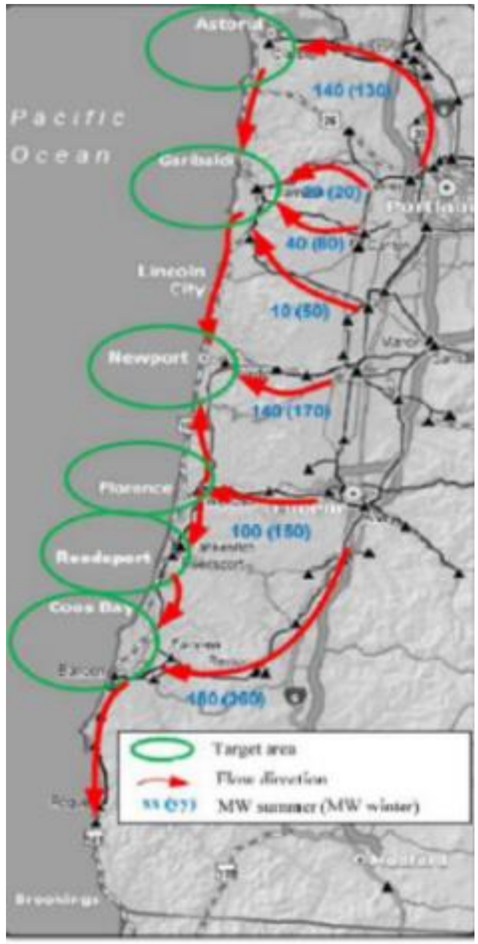


Figure 91 Oregon Transmission Flow (Musial et al., 2019, pg. 46)

The PNNL focused more specifically on grid connections in Oregon, seeking the GW production level that would maximize grid value. The PNNL report supported the NREL findings that a 5 GW project is not feasible at present, as a reversal of the Oregon grid to flow from the coast to the Willamette Valley would be required. However, the study found that (Douville et al., 2020) the coastal grid infrastructure as it stands would be able to accommodate 1 or 2 GW of offshore wind energy, perhaps as much as 3 GW, with only minor reversals.

PNNL identified three potential grid interconnection points in northern and southern Oregon (Douville et al., 2020):

1. Clatsop (Northern Oregon)
2. Takhkenitch (Southern Oregon)
3. Rogue (Southern Oregon)

For any of the three points, transmission flows would need to be reversed to accommodate power coming inland from the coast rather than to the coast from inland. Because actual loading limits are not public information (Douville et al., 2020), the PNNL was unable to determine whether the loads generated by FOWT projects of various GW levels would overwhelm any of the three sites. However, based on the study's analysis of interconnection sites and review of BPA grid interconnection studies, it found that any of the sites would very likely be able to handle at least 2 GW of offshore wind energy without being overwhelmed (Douville et al., 2020).

6.3.2.1.3 Hawaii

Alpha Wind Energy's (Alpha Wind Energy, 2015) two proposed projects in the Oahu Call area-Northwest Oahu and South Oahu-identify three common potential grid interconnection points with South Oahu identifying an additional two. These are:

1. Kahe Power Plant
2. Barbers Point Industrial Area (Several potential points)
3. Wahiawa Substation
4. Honolulu Power Plant (South Oahu only)
5. Kailua Area (South Oahu only)

Figure 92 shows where on the island of Oahu is in relation to each location and the overall Oahu transmission system. The numbered sites in the figure correspond to the numbers on the list above.

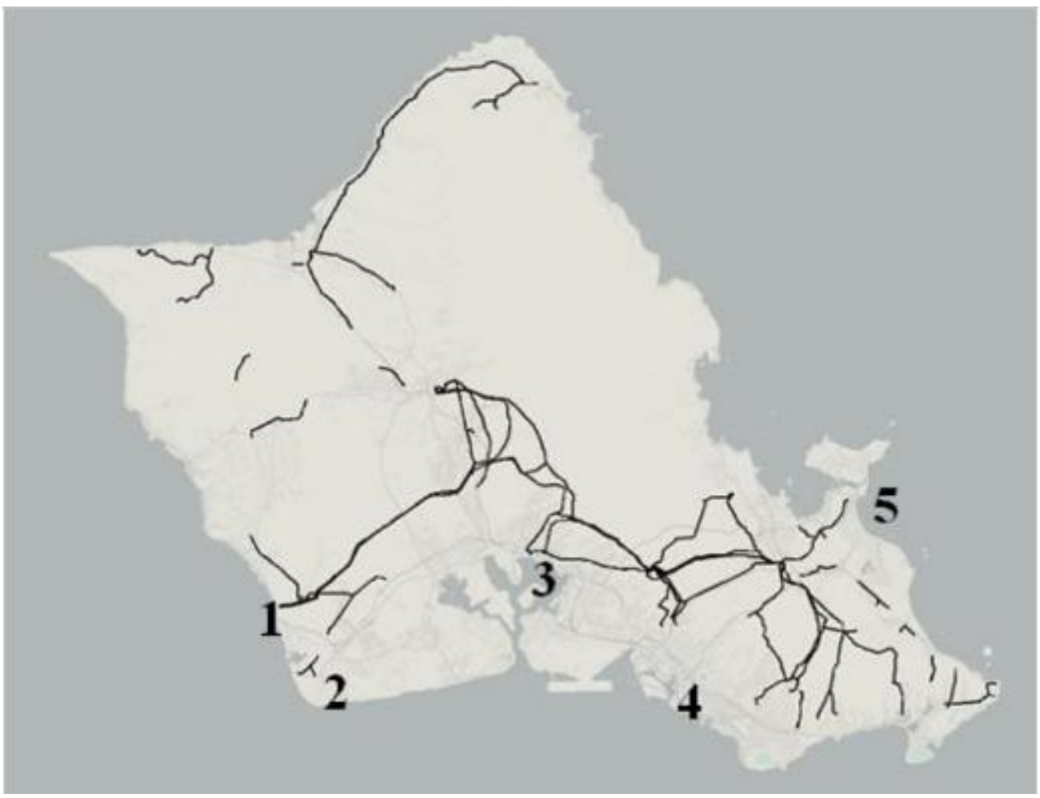


Figure 92 Potential Oahu Grid Interconnection Points (Alpha Wind Energy-Lease Application Oahu South, 2015, pg. 13)

Alpha Wind Energy analyzed the feasibility of each potential grid connection for each potential site. Each potential site has advantages and disadvantages, with the South Oahu project generally having a less complicated path to grid interconnection than the Northwest Oahu path. Table 35 displays Alpha Wind Energy's findings:

Table 35 AWE Assessment of Potential Grid Interconnection Points (Alpha Wind Energy, 2015)

Point	Northwest Oahu Assessment	South Oahu Assessment
Kahe Power Plant	• Most obvious connection • Strong generating capacity, infrastructure • Sea depth, protected coral reefs may pose issues for cable route	• Strong generating capacity, grid infrastructure • Ease of access
Barbers Point Industrial Area	• Strong load, generating capacity • Possibility to construct an additional substation • Sea depth, protected coral reefs may pose issues relating for cable route	• Ease of access • Strong generating capacity • Possibility to construct an additional substation
Wahiawa Substation	• Strong substation capacity, grid infrastructure • Over or underground cable would be necessary from the north coast, which could be controversial	• Strong generating capacity, grid infrastructure • May be unable to route cable through Pearl Harbor due to military objections
Honolulu Power Plant	N/A	• Grid infrastructure strength unclear • Difficult to upgrade if required
Kailua Area	N/A	• Unclear whether grid has sufficient and redundant capacity

Depending on whether the FOWT is located north or south of Oahu, the grid interconnection points have different strengths and weaknesses. The Wahiawa substation, for instance, would be suitable for either project but faces potential issues from a land cable for the northwestern project and from a sea cable for the southern project. Kahe Power Plant and the Barber's Point Industrial area have fewer potential issues for the South Oahu project than the Northwest project based on AWE's assessment. A caveat noted by the application leases, however, is that military restrictions are still largely "unknown" to Alpha Wind Energy (Alpha Wind Energy, 2015) outside of those relating to Wahiawa substation, so the Kahe Power Plant and Barbers Point Industrial Area may not actually be as tenable as the initial assessment found.

The third project interested in the Oahu Call area, Progression (Progression, 2015), does not conduct a full assessment of potential interconnection sites in its lease application, focusing more on the legal process than the logistical one. The Progression lease application notes that because Oahu has used hydroelectric power and has the associated infrastructure already, opportunities to establish a grid connection point should be available.

6.3.2.1.4 Gulf of Maine

While the NREL did not focus on grid connections as part of its economic feasibility assessment of full-scale FOWTs based on Aqua Ventus, it found few opportunities existed for near-shore grid connection (Musial, Beiter, and Nunemaker, 2020). NREL projected in its assessment that based on wind resource availability and technological progress, the LCOE of a full-scale site in place of Aqua Ventus would be some $72/MWh by 2027 and $57/MWh by 2023 (Musial, Beiter, and Nunemaker, 2020). Taking into the cost of required transmission upgrades, however, NREL found that the true LCOE would likely to be at least 10% higher (Musial, Beiter, and Nunemaker, 2020) due to the likelihood of overland or underground connections being required.

The ultimately abandoned Hywind Maine FOWT site planned a "demo" project which would connect to the Maine grid at the substation at Boothbay harbor (Keiser, 2014). Statoil filed an "interconnection request" with the ISO-NE, which found that the substation proposed for interconnection at Boothbay would be tenable "with minor upgrades" (Keiser, 2014). The Hywind "demo" project in Maine was expected to have a total capacity of 12 MW (Keiser, 2014), comparable to that of Aqua Ventus. It is unclear, however, that Boothbay Harbor's substation has the capacity to handle the 600 MW FOWT site Hywind Maine ultimately hoped to deploy.

6.3.2.1.5 Atlantic Coast

According to Musial et al. (2018), there are a few fixed offshore wind projects that are installed or under development along the Atlantic coast. Block Island Wind Farm is the first operating offshore wind farm in state water. There are commercial lease areas in federal waters. Figure 93 shows a map of offshore wind pipeline activity as of March 31, 2019, as well as BOEM Call Areas, for the US Atlantic Coast.

The commitments to grow wind energy from near 5 GW to 20 GW by 2035 posed challenges for grid connection. Integrating this amount of electricity into the existing land-based grid has begun to resonate as a high priority among the many developers, utilities, and state energy organizations. For some states like Massachusetts, New York, and New Jersey, injecting this amount of offshore wind represents up to 30% of their current electricity supply, which is likely to have significant impacts to the land-based grid and transmission system, which needs planning and investment.

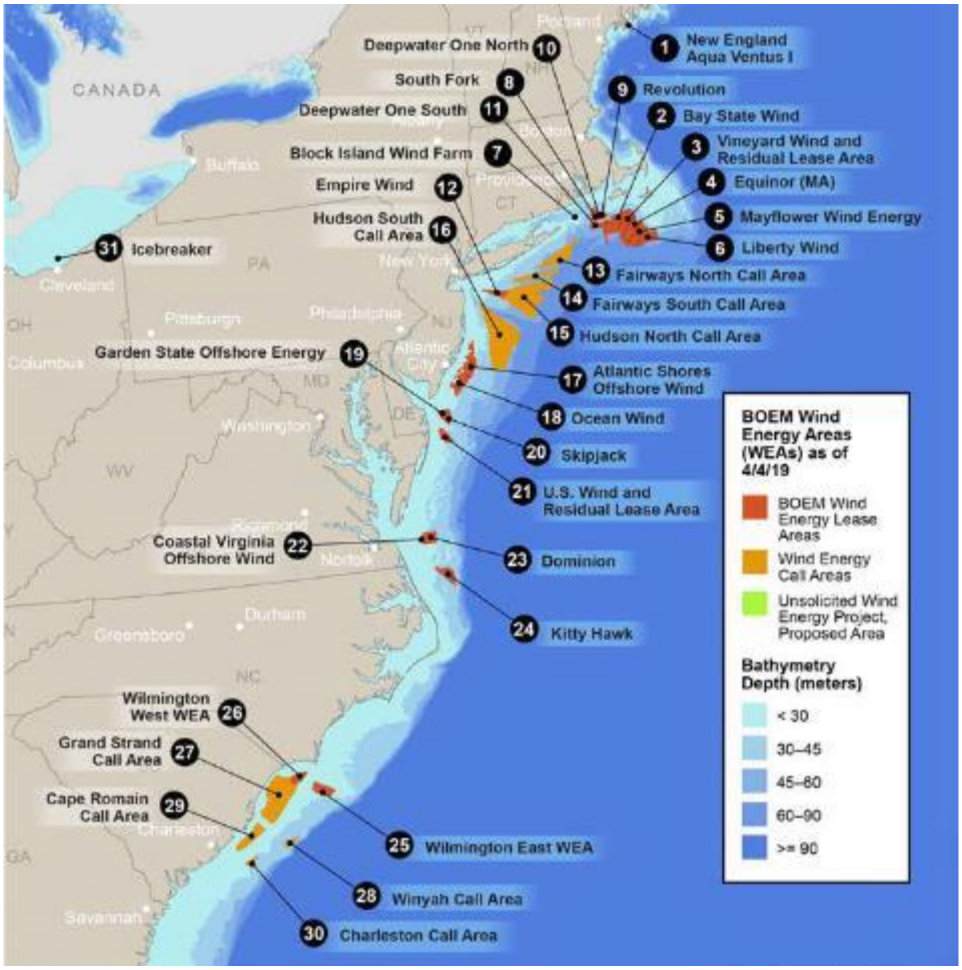


Figure 93 Locations of U.S. offshore wind pipeline activity and Call Areas as of March 2019 -Atlantic Coast (Musial et al., 2018)

In January 2021, the New York State Public Service Commission published the *Initial Report on the New York Power Grid Study* (New York Department of Public Service Staff et al., 2021). The study found that "integrating 9,000 MW of offshore wind generation by 2035 is projected to be achievable without major onshore bulk transmission upgrades beyond expanding Long Island bulk transmission links and likely local upgrades in New York City."

6.4 LOCAL REGULATORY ENVIRONMENT

As is the case in any new industry, local regulatory environments have the ability to facilitate or hamper progress. Because uncertainty for developers abounds in any new industry, a friendly and proactive regulatory regime for FOWTs is one that takes steps to reduces uncertainty. ABSG found after reviewing assessments of regulatory conditions in active or potential WEAs that the following conditions make for a more certain, more favorable regulatory environment:

- **Stability (Heidari, 2017):** Stable, predictable, and consistent regulations help to reduce uncertainty. If regulations often change or are inconsistent, developers cannot gauge what practices will or will not be acceptable in the future. They will fear a sudden change in regulation that would make their operations less profitable. Stable regulations reduce uncertainty by letting developers know what rules they are going to have to follow in the present and in the near and long term, making FOWT projects in the area more attractive to investors.

- **Long-Term State Patronage:** Together with stability in reducing uncertainty is a long-term commitment by the state to authorize utility companies to purchase wind power. Multi-year contracts being made available reduce uncertainty for developers by ensuring a stream of revenue for a longer period (Collier, 2017). Fixed FOWT costs are high and FOWTs tend to have long lifecycles. As such, longer-term contracts guaranteeing payment are needed to offset higher short-term costs and ensure future cash flows.
- **Targets**: Governments around the world that have been successful in launching FOWT industries have been diligent about setting and committing to targets for renewable energy production (Sathe et al., 2020). A state that sets a target level of energy production by a certain date sends a message to developers that they are serious about producing offshore wind energy in the long term. Target-setting assures developers in the nascent and high fixed cost FOWT industry that future cash flows can be depended on.
- **Activities in State Waters**: States that have deployed or are preparing to deploy FOWTs in state waters show they are eager to develop and accommodate Floating Wind. Whether deploying tests or actively trying to lease out space in state waters, states that are taking action to implement floating wind in their own waters show an inclination towards establishing regulations favorable to the FOWT industry, and potentially a greater willingness to work with developers should some regulations already in place prove unfavorable.
- **Full Cost Recovery (Collier, 2017)**: Full cost recovery enables utility companies to purchase wind power and pass any unexpected increase costs to ratepayers through price increases. Current laws in all areas of interest keep the burden on the utility companies, forbidding them from raising prices should wind power drive up their costs unexpectedly. If utility companies can pass these costs onto consumers rather than having to bear costs internally, they will lose less money directly if FOWT production falls short of expectations. The utility companies would then be more likely to take the risk of upstarting a FOWT industry. While such a law would make for a more friendly regulatory environment, it also may be politically unpopular and therefore difficult to implement. Such a bill was proposed and defeated in Oregon in 2015.

In addition to the government-established conditions above that make a local regulatory environment amenable to FOWTs, stakeholder barriers also play a role in making a regulatory condition more or less favorable. Stakeholders in potential WEAs who may object to FOWTs include:

- Fisheries and fishers, who may object to FOWT establishment because the FOWTs may need to exclude fishing activities

- The Department of Defense, who in the Diablo Canyon and Morro Bay call areas object to the implementation of FOWTs due to Naval exercises taking place in those vicinities
- Commercial shipping stakeholders, as ship routes would likely need to be re-routed around FOWTs

Table 36 lists the findings from reviewing assessments of regulatory conditions in each of the four areas of interest. The areas of interest are assigned a favorability rating based on how proactive their regulatory regime is in accommodating FOWTs and the degree to which stakeholder barriers pose a difficulty. One of three ratings is given to each area of interest:

- A "favorable" rating indicates that a state is being proactive in establishing a productive environment for FOWT developers, and stakeholder barriers are negligible or navigable
- A "neutral" rating indicates that a state is doing nothing to help or hinder the development of floating wind and/or stakeholder barriers are a modest challenge
- An "unfavorable" rating indicates that a state is actively fighting floating wind development and/or stakeholder barriers will be extremely difficult for developers to surmount

Table 36 Regulatory Environment Favorability Assessment by Area of Interest

State	Proactivity	Stakeholder Barriers	Favorability Rating
California	State has set an energy portfolio target of 60% renewable energy by 2030, 100% renewable energy 2045 (NCSL, 2020) CADEMO Floating Offshore Wind Demonstration Project projected to be deployed in state waters & operational by 2025	Navy objects (Nikolewski, 2018) to FOWT operations in central and southern California, including Diablo Canyon and Morro Bay areas, due to concerns over interference with training and operations In September 2020, the Navy provided a statement that the WEA in the vicinity of Morro Bay impacts training at an acceptable risk; but the assessment is contingent upon a long-term moratorium on further wind energy development in military operating areas. The statement also provided a willingness to work with interested parties for 3GW of energy from offshore wind. (Braithwaite, 2020) Fishing, shipping, concerns	Favorable (State has ambitious goals and projects in state waters, but difficult stakeholder barriers to negotiate in some areas.)

State	Proactivity	Stakeholder Barriers	Favorability Rating
Oregon	State has set a target energy portfolio of 25% renewable energy by 2025, 50% renewable energy by 2040	Fishing, shipping, concerns	Favorable
Hawaii	State has set a target energy portfolio of 100% renewable energy by the year 2045	Department of Defense has not explicitly forbidden the development of FOWT sites, but proposed projects do overlap with some naval training areas. Progression (Progression, 2015) plans to site a project while "accommodating military interests" as much as possible. Alpha Wind Energy (Alpha Wind Energy, 2015), in its proposed lease, reports "consulting with the U.S. Navy" but that the "results of consultation are not conclusive" Fishing, shipping, concerns	Favorable
Maine	State has set a target energy portfolio of 80% renewable energy by 2030 100% renewable energy by the year 2050. Aqua Ventus project deployed in state waters	Fishing, shipping, concerns	Favorable
Atlantic Coast	Atlantic coast states including Massachusetts, North Carolina, South Carolina, New York, New Jersey, Virginia, Georgia, Maryland, and Rhode Island are active in wind energy development both in state and federal waters	Fishing, shipping, concerns	Favorable

6.5 ECONOMIC FINDINGS

ABSG reviewed research and studies related to the economic feasibility of FOWT sites on the U.S. OCS. Below are four tables, one for each of California, Oregon, Hawaii, and Maine, listing the main findings from the examined research for each of the following factors:

- Levels of wind resources
- Projected technological advancements
- Availability of local infrastructure for fabrication & installation
- Availability of grid connections near FOWT sites
- Proactivity of regulatory regime
- Presence of stakeholder barriers

Factors for each state are given an overall feasibility assessment based on whether a FOWT site would be feasible in terms of that specific factor. Different factors may have different feasibility levels within and across states. All areas of interest have enough wind resources to make FOWT sites feasible, for instance, but they vary in the strength of their local infrastructures and grid interconnection viability. One of two feasibility scores will be given for each factor:

- Feasible, indicating that FOWT projects are feasible with respect to the factor in question with little to no change
- Somewhat feasible, indicating large necessary changes or other large but surmountable obstacles being needed for FOWT feasibility

Table 37 Final Economic Feasibility Assessment of California

Factor	Findings	Overall Feasibility Assessment
Wind Resources	• All three California call areas have sufficiently high levels of wind resources • Northern call area has stronger wind resources than central call areas	Feasible
Projected Technological Advancements	• Technological advancements projected to increase the capacity of FOWTs in California and reduce LCOE	Feasible
Availability of Local Infrastructure for fabrication and installation	• All three California Call areas have access to ports with requisite navigation channel depth and width • Northern California call area deep water port of Humboldt Bay has ample space, but faces seasonality issues and lacks rail/highway access • Central California call areas have several deep water ports with requisite navigation channel width and depth, which are available year-round, but space is more limited than in Northern California and port owners have indicated reluctance to host assembly/fabrication operations	Somewhat feasible; infrastructure in all locations will require upgrades

Factor	Findings	Overall Feasibility Assessment
Availability of Grid Connections	• Diablo Canyon, Morro Bay best options for grid connection due to existing capacities • Large investment needed for call area near Humboldt Bay to have a feasible grid connection	Feasible
Proactive Regulatory Regime	• California has set renewable energy targets • California has deployed CADEMO project in state waters	Feasible
Stakeholder Barriers	• Navy objection to Diablo Canyon and portion Morro Bay Call areas • Fishing, shipping/navigation concerns	Somewhat feasible. Navy has signaled willingness to negotiate (Braithwaite, 2020)

Table 38 Final Economic Feasibility Assessment of Oregon

Factor	Findings	Overall Feasibility Assessment
Wind Resources	• Oregon OCS has sufficiently high levels of wind resources • Southern Oregon has stronger wind resources than northern Oregon	Feasible
Projected Technological Advancements	• Technological advancements projected to increase the capacity of FOWTs in Oregon and reduce LCOE	Feasible
Availability of Local Infrastructure for fabrication and installation	• Astoria, Coos Bay likeliest assembly ports • Both would modest upgrades	Feasible
Availability of Grid Connections	• Grid connections available in northern and southern Oregon • Limited interconnection capacity due to Oregon grid's current flow directions setup of	Feasible (depending on the scale of project)
Proactive Regulatory Regime	• State has set renewable energy targets	Feasible
Stakeholder Barriers	• Fishing & shipping/navigation concerns	Feasible

Table 39 Final Economic Feasibility Assessment of Hawaii

Factor	Findings	Overall Feasibility Assessment
Wind Resources	• Hawaii call area has sufficiently high levels of wind resources	Feasible
Projected Technological Advancements	• Technological advancements projected to increase the capacity of FOWTs in Hawaii and reduce LCOE	Feasible
Availability of Local Infrastructure for fabrication and installation	• Honolulu, Barbers point has the capacity to serve as assembly/fabrication and O&M ports • Concerns that the ports lack upland space	Somewhat feasible (requires upgrades)
Availability of Grid Connections	• Several potential grid connections available	Feasible (military concerns)
Proactive Regulatory Regime	• State has set renewable energy targets	Feasible
Stakeholder Barriers	• Military may object to certain sites within Call area due to operational concerns • Concerns over coral reefs near Honolulu • Shipping/navigation concerns	Feasible (military concerns)

Table 40 Final Economic Feasibility Assessment of Maine

Factor	Findings	Overall Feasibility Assessment
Wind Resources	• Gulf of Maine OCS has sufficiently high wind resources	Feasible
Projected Technological Advancements	• Technological advancements projected to increase the capacity of FOWTs in Maine and reduce LCOE	Feasible
Availability of Local Infrastructure for fabrication and installation	• Searsport to be evaluated for viability as a FOWT hub • Smaller ports available for O&M	Somewhat feasible (more research needed; assessments of Searsport underway by the State of Maine)
Availability of Grid Connections	• Few grid connections available near-shore • Pilot Hywind-Maine project intended to connect to Maine grid at Boothbay	Somewhat feasible (grid connections are possible, but are expected to considerably raise costs)
Proactive Regulatory Regime	• State has set renewable energy target • FOWT project deployed in state water	Feasible
Stakeholder Barriers	• Fishing & Shipping/Navigation concerns	Feasible

7 FINAL RECOMMENDATIONS

In summary, based on the technological, environmental, and economic assessment of FOWT projects and research presented in this report, ABSG recommends the following additional research and actions to further the advancement of FOWTs on the OCS:

- Currently, the existing AWEA Offshore Compliance Recommended Practices (AWEA OCRP, 2012) are outdated. AWEA is developing a new set of recommendations practices, which they plan on publishing in late 2021. The recommended practices will include recommendations for floating offshore wind systems, deployment, and operation. BOEM should be aware and track the development of the recommended practices, associated standards and guidelines by AWEA/ANSI and other standards development organizations and investigate the incorporation of the documents into regulation by reference.
- BOEM should follow current ongoing research projects detailed in this report on technological, environmental, and economic issues and use project results to inform the development and environmental reviews of WEAs, and the technical and environmental reviews of Site Assessment Plans, Construction and Operations Plans, Facility Design Reports, Fabrication, and Installation Reports.
- BOEM should consider conducting further studies to identify fishing areas in and around current and future Call areas and assess potential impacts to fishing. The research should include types of fishing that occurs, species targeted, fishing gear used, depths fished using certain gear, and space required for the types of fishing.
- BOEM should coordinate with NOAA Fisheries, USCG Waterways Management, state fisheries, and the fishing industry using all available means, including AIS/VMS data, vessel trip reports, and other fisheries information to determine fishing transit routes and high- and low-density fishing areas and impacts of fishery displacement.
- BOEM should collaborate with wind farm developers, NOAA, state fisheries, and the fishing industry to research wind farm designs and fishing methods that accommodate fishing within wind farms.
- BOEM should ensure that developers consult with the U.S. Coast Guard and waterway users to consider project-specific factors such as vessel traffic patterns and fishing activities that occur in and around the FOWT project sites to inform the design of mooring systems and dynamic power cables in order to minimize navigation impacts.
- BOEM should encourage the State of Maine to work with USCG Waterways Management on vessel traffic and safety of navigation issues as the state seeks to identify the specific site for the proposed research array to avoid impacts to navigation and shipping.
- BOEM should request the USCG Waterways Management conduct Port Access Route Studies (PARS) for central and northern California, Oregon, Hawaii, and the Gulf of Maine

to identify and analyze current maritime traffic, routes, and vessel traffic densities to determine the potential impacts from offshore wind development. BOEM could use the results of the PARS to evaluate current and future Call areas and WEAs, including the proposed Maine floating offshore wind research array.

- BOEM should conduct additional research into infrastructure requirements for FOWT development (fabrication, construction, assembly, operations & maintenance) to include potential ports, supply chain, navigation, and transmission grid connections. This research would identify and promote technical solutions, improve the interactions between the industry and government agencies, facilitate the development of renewable energy supply chains, and continue to assess the effects of development on the environment and economy.

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APPENDIX A: WORLDWIDE INSTALLED AND PROPOSED FOWTS

This appendix provides a summary of projects installed and projects under planning/development worldwide. The projects installed worldwide are summarized in Table A-1. The projects under planning/development worldwide are summarized in Table A-2. The tables are organized by country and year and provide the project design type, location, turbine, designer, stage of development and, status of the project.

Table A-1 FOWT Projects – Worldwide, Installed

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
U.S.							
2013	VolturnUS 1:8	VolturnUS, semi-submersible	Offshore Castine, Maine, US	Renewegy 20 kW	University of Maine	Small scale prototype demo	Decommissioned in 2014
Japan							
2013	Kabashima	Haenkaze, Toda Hybrid spar	Offshore Kabashima, Goto City, Japan	Hitachi 2 MW downwind	Toda	Prototype demo	Relocated in 2015
2015	Sakiyama	Haenkaze, Toda Hybrid spar	Offshore Sakiyama, Fukue Island, Japan	Hitachi 2 MW downwind	Toda	Prototype demo	Operational
2013	Fukushima FORWARD Phase 1	Fukushima Kizuna, Advanced Spar	Offshore Fukushima, Japan	66kV, 25MVA Floating Substation	Fukushima Offshore Wind Consortium	Prototype demo	Operational
2013	Fukushima FORWARD Phase 1	Fukushima Mira, compact semi-submersible	Offshore Fukushima, Japan	Hitachi 2 MW downwind	Fukushima Offshore Wind Consortium	Prototype demo	Operational
2015	Fukushima FORWARD Phase 2	Fukushima Shimpuu, V-shape Semi-Submersible	Offshore Fukushima, Japan	MHI 7 MW	Fukushima Offshore Wind Consortium	Prototype demo	Being dismantled
2016	Fukushima FORWARD Phase 2	Fukushima Hamakaze, Advanced Spar	Offshore Fukushima, Japan	Hitachi 5 MW downwind	Fukushima Offshore Wind Consortium	Prototype demo	Operational
2019	Hibiki	Ideol Damping Pool, barge	Offshore Kitakyushu, Japan	Aerodyn SCD 3 MW, 2 bladed	Ideol	Prototype demo	Operational
Denmark							
2008	Poseidon 37 Demonstrator	Poseidon multi-turbine semi-submersible	Offshore Lolland, Denmark	33 kW	Floating Power Plant	Prototype demo	Ended 2013

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
Norway							
2009	Hywind Demo	Hywind Spar	Offshore Karmøy, Norway	Siemens 2.3 MW	Equinor	Prototype demo	Operational, sold to Unitech in January 2019
Potrugal							
2011	WindFloat 1 (WF1)	WindFloat semi-submersible	Offshore Aguçadoura, Portugal	Vestas 2 MW	Principle Power	Prototype demo	Decommissioned in 2016, Relocated in 2018
2020	WindFloat Atlantic (WFA)	WindFloat semi-submersible	Offshore Viana do Castelo, Portugal	MHI Vestas 3×8.4 MW	Principle Power	Pre-commercial	Operational
Sweden							
2015	SeaTwirl S1	SeaTwirl Spar	Offshore Lysekil, Sweden	30 kW Vertical Axis Wind Turbine	SeaTwirl	Small Scale prototype demo	Operational
UK							
2017	Hywind Scotland	Hywind Spar	Offshore Peterhead, Scotland, UK	Siemens 5×6 MW	Equinor	Pre-commercial	Operational
2020	Kincardine	WindFloat semi-submersible	Offshore Kincardineshire, Scotland, UK	MHI Vestas 2 MW (former WF1), MHI Vestas 5×9.5 MW	Principle Power	Pre-commercial	WF1 relocated and operational in 2018, the five 9.5 MW turbines are under construction
France							
2018	Floatgen	Ideol Damping Pool, barge	Offshore Le Croisic, France	Vestas 2 MW	Ideol	Prototype demo	Operational
Spain							
2019	W2Power 1:6 Scale	EnerOcean W2Power semi-submersible	Offshore Gran Canaria, Spain	2×100 kW twin-rotor	EnerOcean	Small scale prototype demo	Decommissioned in 2019
2020	BlueSATH	Saitec SATH 1:6	Offshore Santander, Spain	Aeolos 30 kW	Saitec	Small scale prototype demo	Operational

Table A-2 FOWT Projects – Worldwide, All

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
U.S.							
2013	VolturnUS 1:8	VolturnUS, semi-submersible	Offshore Castine, Maine, US	Renewegy 20 kW	University of Maine	Small scale prototype demo	Decommissioned in 2014
2013	WindFloat Pacific (WFP)	WindFloat semi-submersible	Offshore Coos Bay, Oregon, US	5×6 MW	Principle Power	Pre-commercial	Cancelled
2023	New England Aqua Ventus I	VolturnUS semi-submersible	Offshore Monhegan Island in the Gulf of Maine, US	12 MW	University of Maine	Prototype demo	Expected to be completed in 2023
2024	RedWood Coast	WindFloat semi-submersible	Offshore Humboldt County, California, US	100 – 150 MW	Principle Power	Commercial	BOEM Call Area Expected to come online in 2024
2025	Progression South	WindFloat semi-submersible	Offshore Oahu, Hawaii, US	400 MW	Principle Power	Commercial	BOEM Call Area Plan proposed
2025	CADEMO	SBM TLP/ Saitec SATH	Offshore Vandenberg, California, US	4×12 MW	SBM Offshore/ Saitec	Pre-commercial	Planning for operation by 2024/25
2026	Castle Wind	No data	Offshore Morro Bay, California, US	1000 MW	No data	Commercial	BOEM Call Area Planning for 2026
2027	AWH Oahu Northwest	WindFloat semi-submersible	Offshore Oahu, Hawaii, US	400 MW	Principle Power	Commercial	BOEM Call Area Plan proposed
2027	AWH Oahu South	WindFloat semi-submersible	Offshore Oahu, Hawaii, US	400 MW	Principle Power	Commercial	BOEM Call Area Plan proposed
No data	Diablo Canyon	No data	Offshore Diablo Canyon, California, US	No data	No data	Commercial	BOEM Call Area
No data	Mayflower Wind	No data	Offshore Massachusetts, US	10+ MW	Atkins	Prototype demo	Planning
Japan							
2013	Kabashima	Haenkaze, Toda Hybrid spar	Offshore Kabashima, Goto City, Japan	Hitachi 2 MW downwind	Toda	Prototype demo	Relocated in 2015

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
2015	Sakiyama	Haenkaze, Toda Hybrid spar	Offshore Sakiyama, Fukue Island, Japan	Hitachi 2 MW downwind	Toda	Prototype demo	Operational
2013	Fukushima FORWARD Phase 1	Fukushima Kizuna, Advanced Spar	Offshore Fukushima, Japan	66kV, 25MVA Floating Substation	Fukushima Offshore Wind Consortium	Prototype demo	Operational
2013	Fukushima FORWARD Phase 1	Fukushima Mira, compact semi-submersible	Offshore Fukushima, Japan	Hitachi 2 MW downwind	Fukushima Offshore Wind Consortium	Prototype demo	Operational
2015	Fukushima FORWARD Phase 2	Fukushima Shimpuu, V-shape Semi-Submersible	Offshore Fukushima, Japan	MHI 7 MW	Fukushima Offshore Wind Consortium	Prototype demo	Being dismantled
2016	Fukushima FORWARD Phase 2	Fukushima Hamakaze, Advanced Spar	Offshore Fukushima, Japan	Hitachi 5 MW downwind	Fukushima Offshore Wind Consortium	Prototype demo	Operational
2019	Hibiki	Ideol Damping Pool, barge	Offshore Kitakyushu, Japan	Aerodyn SCD 3 MW, 2 bladed	Ideol	Prototype demo	Operational
2021	Goto City	Toda Hybrid spar	Offshore Kabashima, Goto City, Japan	22 MW	Toda	Prototype demo	Planned for 2021, extension of the Sakiyama project
2023	Acacia	Ideol Damping Pool, barge	Offshore Japan	No Data	Ideol	Commercial	Construction is currently set for 2023
No Data	Nezzy Demonstrator	SCD nezzy Semi-Submersible	Offshore Japan	Aerodyn SCD 6 MW, 2 bladed	SCD Technology	Prototype demo	No Data
Korea							
2022	Donghae TwinWind	Hexicon multi-turbine semi-submersible	Offshore Ulsan, Korea	200 MW	Hexicon	Commercial	Planning for deployment from 2022
2020	Ulsan 750kW Floating Demonstrator	Semi-submersible	Offshore Ulsan, Korea	750 kW	University of Ulsan	Prototype demo	Expected to be completed in 2020
2020	Ulsan Prototype	No Data	Offshore Ulsan, Korea	5 MW	No Data	Prototype demo	Expected to be complete by 2020
2023	Gray Whale	No Data	Offshore Ulsan, Korea	500 MW	No Data	Commercial	Targeted for completion by 2023
2024	KNOC (Donghae 1)	Hywind Spar	Offshore Ulsan, Korea	200 MW	Equinor	Commercial	Planning for 2024

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
No Data	KFWind	WindFloat semi-submersible	Offshore Ulsan, Korea	500 MW	Principle Power	Commercial	Planning
No Data	White Heron	No Data	Offshore Ulsan, Korea	200 MW	No Data	Commercial	Planning
Denmark							
2008	Poseidon 37 Demonstrator	Poseidon multi-turbine semi-submersible	Offshore Lolland, Denmark	33 kW	Floating Power Plant	Prototype demo	Ended 2013
Norway							
2009	Hywind Demo	Hywind Spar	Offshore Karmøy, Norway	Siemens 2.3 MW	Equinor	Prototype demo	Operational, sold to Unitech in January 2019
2020	TetraSpar Demo	Stiesdal TetraSpar, Spar	Offshore Karmøy, Norway	Siemens Gamesa 3.6 MW	Stiesdal	Prototype demo	Installation scheduled for 2020
2021	SeaTwirl S2	SeaTwirl Spar	Offshore Haugaland, Norway	1 MW Vertical Axis Wind Turbine	SeaTwirl	Prototype demo	Planned for installation in 2021
2022	Hywind Tampen	Hywind Spar	Snorre and Gullfaks offshore fields, offshore Norway	Siemens Gamesa 11×8 MW	Equinor	Pre-commercial	Scheduled to be commissioned in late 2022
2022	Flagship Demo	OO-Star semi-submersible	Offshore Karmøy, Norway	10 MW	Iberdrola	Prototype demo	Planning for 2022
2023	NOAKA	No Data	Offshore Norway	No Data	No Data	No Data	First production expected in 2023
Portugal							
2011	WindFloat 1 (WF1)	WindFloat semi-submersible	Offshore Aguçadoura, Portugal	Vestas 2 MW	Principle Power	Prototype demo	Decommissioned in 2016, Relocated in 2018
2020	WindFloat Atlantic (WFA)	WindFloat semi-submersible	Offshore Viana do Castelo, Portugal	MHI Vestas 3×8.4 MW	Principle Power	Pre-commercial	Operational
Sweden							
2015	SeaTwirl S1	SeaTwirl Spar	Offshore Lysekil, Sweden	30 kW Vertical Axis Wind Turbine	SeaTwirl	Small Scale prototype demo	Operational
UK							

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
2017	Hywind Scotland	Hywind Spar	Offshore Peterhead, Scotland, UK	Siemens 5×6 MW	Equinor	Pre-commercial	Operational
2017	Hexicon Dounreay Trì project	Hexicon multi-turbine semi-submersible	Offshore Dounreay, Scotland, UK	2×5 MW	Hexicon	Prototype demo	Project halted
2020	Kincardine	WindFloat semi-submersible	Offshore Kincardineshire, Scotland, UK	MHI Vestas 2 MW (former WF1), MHI Vestas 5×9.5 MW	Principle Power	Pre-commercial	WF1 relocated and operational in 2018, the five 9.5 MW turbines are under construction
2021	Atlantis Ideol	Ideol damping pool, barge	Offshore UK	100 MW	Ideol	Pre-commercial	Planning
No Data	TLPWind UK	TLPWind TLP	Offshore UK	5 MW	Iberdrola	Prototype demo	Project halted
Ireland							
2022	AFLOWT	Hexafloat, semi-submersible	Offshore the Irish west coast, Ireland	6 MW	Saipem	Prototype demo	Deployment is planned for 2022
No data	Emerald	WindFloat semi-submersible	Offshore Kinsale, Ireland	100 MW	Principle Power	Pre-commercial	Planning
Germany							
2017	Gicon SOF	Gicon TLP	Baltic Sea, Germany	Siemens 2.3 MW	GICON	Prototype demo	Planned and postponed
France							
2018	Floatgen	Ideol Damping Pool, barge	Offshore Le Croisic, France	Vestas 2 MW	Ideol	Prototype demo	Operational
2021	EolMed	Ideol Damping Pool, barge	Offshore Gruissan, Mediterranean Sea, France	Senvion 4×6.2 MW	Ideol	Pre-commercial	Expected operating by late 2020/early 2021
2021	Provence Grand Large (PGL)	SBM TLP	Offshore Napoleon beach, Mediterranean Sea, France	Siemens Gamesa 3×8.4 MW	SBM Offshore	Pre-commercial	Expected to be commissioned in 2021
2022	Golfe du Lion (EFGL)	WindFloat semi-submersible	Offshore Leucate-Le Barcarès, Mediterranean Sea, France	MHI Vestas 3×10 MW	Principle Power	Pre-commercial	Commissioning scheduled for 2022
2022	Groix & Belle-Ile	Sea Reed semi-submersible	Offshore Brittany, France	MHI Vestas 3×9.5 MW	Naval Energies	Pre-commercial	Commissioning scheduled for 2022

Year	Project Name	Floating Substructure Design, Type	Location	Turbine, Power	Designer	Development Stage	Status
No Data	Eolink Demonstrator	Eolink semi-submersible	Offshore Le Croisic, France	5 MW	Eolink	Prototype demo	Planning
Spain							
2019	W2Power 1:6 Scale	EnerOcean W2Power semi-submersible	Offshore Gran Canaria, Spain	2×100 kW twin-rotor	EnerOcean	Small scale prototype demo	Decommissioned in 2019
2020	BlueSATH	Saitec SATH 1:6	Offshore Santander, Spain	Aeolos 30 kW	Saitec	Small scale prototype demo	Operational
2020	PivotBuoy 1:3 Scale	PivotBuoy TLP	Offshore Canary Islands, Spain	Vestas 200kW	X1 Wind	Prototype demo	Planned for installation in 2020
2020	FLOCAN5	Cobra semi-spar	Offshore Canary Islands, Spain	5×5 MW	Cobra	Pre-commercial	Expected entry into Operation 2020
2021	DemoSATH	Saitec SATH	Offshore Basque, Spain	2 MW	Saitec	Prototype demo	Marine operations are planned by the end of 2021
No Data	Parque Eólico Gofio	No Data	Offshore Gran Canaria, Spain	4×12.5 MW	Greenalia	Pre-commercial	Planning
No Data	Balea	No Data	Basque Country, Spain	26 MW	No Data	Pre-commercial	Planning
No Data	WunderHexicon	No Data	Offshore Gran Canaria, Spain	No Data	Hexicon	No Data	Planning
Taiwan							
No Data	Taihai Taoyuan (W1N)	No Data	Offshore Taiwan	No Data	No Data	Commercial	Project cancelled
No Data	W1S/W2S/ W2N/W3	No Data	Offshore Taiwan	No Data	No Data	Commercial	No Data

APPENDIX B: FOWT PROJECT SUMMARIES

Figure A-1 Hywind Demo offshore Karmøy, Norway

HYWIND DEMO (ZEFYROS) PROJECT

Detailed information on the "Hywind Demo (Zefyros)" project is summarized in Table A-3. Hywind Demo is the world's first full scale floating wind turbine that is still operational.

In 2009, Equior installed the Hywind Demo offshore Karmøy, Norway. Through eight years of successful operations, the demo has confirmed and verified the Hywind concept. The test turbine has been sold to Unitech for further research. From February 1, 2019, the turbine was renamed "UNITECH Zefyros by Hywind Technology".

The Hywind Demo is the world's first full-scale floating offshore wind turbine.

Table A-3 Hywind Demo (Zefyros) Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2009	Hywind Spar	Equinor	Siemens 2.3 MW	Spread mooring system	220 meters (722 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Karmøy, Norway	10 kilometers (6.2 miles)	Equinor	Prototype demo	Operational, sold to Unitech in January 2019	
Fabrication & Installation					
Hull	**Mooring and Anchor**	**Power Cable**	Hull was towed horizontally from the construction yard in Pori, Finland, to Norway, then was upended and filled with olivine sand on April 26, 2009. Tower, nacelle, and rotor was partially pre-assembled onshore in Dusavika. Then pre-assembled turbine and tower were mounted on the floating substructure in-shore in the Åmøy Fjord near Stavanger in May 2009. Assembled floating wind turbine was towed upright to offshore site and connected to the mooring system in June 2009. The turbine was connected to the local grid in August 2009.		
Steel hull was constructed by Technip in Finland and towed to Stavanger.	Three-line mooring system (wire/chain, clump weight) and Vryhof drag embedded anchors	Nexans Norway produced and laid the 13.6 kilometers (8.5 miles) long 15 MW 24 kV power cable to land.			
Site Condition			**Estimated Cost**		
Experienced wind speed of 40 m/s and maximum wave height of 19 meters			NOK 400 million (US$71 million)		

Hywind Demo (Zefyros) Project

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WINDFLOAT 1 (WF1) PROJECT

Figure A-2 The 2MW WindFloat 1 (WF1)

Detailed information on the "WindFloat 1 (WF1)" project is summarized in Table A-4.

The 2MW WindFloat 1 (WF1) is the world's second full-scale FOWT and the first full-scale prototype of WindFloat. It was developed by Principle Power, along with its project partners EDP, Repsol, Portugal Ventures, and A. Silva Matos.

WindFloat 1 was decommissioned in 2016. The 2MW WF1 floating substructure was sold and relocated in 2018 and became the first installed in the Kincardine FOWF.

Table A-4 WindFloat 1 (WF1) - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2011</td><td>WindFloat semi-submersible</td><td>Principle Power</td><td>Vestas 2 MW</td><td>Spread mooring system</td><td>49 meters (161 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Aguçadoura, Portugal</td><td>5 kilometers (3.1 miles)</td><td>WindPlus S.A., led by Energias de Portugal (EDP)</td><td>Prototype demo</td><td colspan="2">Decommissioned in 2016, relocated in 2018</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">After onshore assembly and pre-commissioning of the wind turbine and floating substructure at the Lisnave facility near Setubal, Portugal, the FOWT was loaded-out and wet-towed to the offshore site. The pre-laid mooring lines were connected to the hull. Dynamic cable was hooked-up to the hull and connected to the existing export cable.</td></tr>
<tr><td>Hull was fabricated by A. Silva Matos (ASM), a local company specializing in fabrication of wind turbine towers.</td><td>Four-line mooring system (chain/wire) and Vryhof drag embedment anchors</td><td>Existing static cable to shore and the Portuguese grid.
500 meters long section of new subsea dynamic electrical cable by JDR.</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">1-year significant wave height 7 meters
50-year significant wave height 11 meters
Experienced waves exceeded 17 meters and winds of over 31 m/s (60 knots).</td><td colspan="3">EUR 20 million (US$25 million)</td></tr>
</table>

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VOLTURNUS 1:8 PROJECT

Figure A-3 The VolturnUS 1:8

Detailed information on the "VolturnUS 1:8" project is summarized in Table A-5.

The VolturnUS 1:8 is a geometrically 1:8-scale of a 6 MW floating wind turbine design with a concrete floating substructure and a fiber reinforced plastic (FRP) tower. The project is the culmination of collaborative research and development conducted by the University of Maine-led DeepCwind Consortium.

The VolturnUS 1:8 floating semi-submersible wind turbine was the first grid connected offshore turbine in the United States. This project represents the first concrete-composite (Hull-tower) floating wind turbine deployed in the world.

Table A-5 VolturnUS 1:8 - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2013	VolturnUS, semi-submersible	University of Maine	Renewegy 20 kW	Spread mooring system	27.4 meters (90 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Castine, Maine, US	~ 330 meters (1,000 feet)	DeepCwind Consortium	Small scale prototype demo	Decommissioned in 2014	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	The assembly of the hull, tower, and turbine all took place on land at the Cianbro Modular Manufacturing Facility in Brewer, Maine. The entire unit fully assembled was towed with a single tug boat and an assistance vessel. Upon arrival in Castine, the unit was hooked to preinstalled chain moorings connected to preset drag anchors.		
The patented VolturnUS 1:8 was designed and built at UMaine, assembled at Cianbro's facility in Brewer.	Three catenary chain moorings anchored to the seabed with Vryhof drag embedment anchors	Wind turbine was connected through an undersea cable to the Central Maine Power electricity grid.			
Site Condition			**Estimated Cost**		
Operational significant wave height 0-0.75 meters 50-year significant wave height 1.3 meters 50-year 10 mins wind speed at hub height 14.1 m/s 500-year significant wave height 1.5 meters 500-year 10 mins wind speed at hub height 15.9 m/s			US $12 million Department of Energy (DOE) investment		

<u>VolturnUS 1:8 Project</u>

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SAKIYAMA PROJECT

Figure A-4 Sakiyama 2MW FOWT

Detailed information on the "Sakiyama" project is summarized in Table A- 6.

The "Sakiyama 2MW Floating Offshore Wind Turbine" called Haenkaze is the first grid connected full scale floating wind turbine in Japan. It was installed offshore Kabashima in 2013 by Toda Corporation and other consortium members. After the two-year demonstrative operation, Haenkaze was transferred to 5 kilometers off the coast of Sakiyama Fukue Island, which is about 10 kilometers from the original site.

Haenkaze is the world's first floating wind turbine with a hybrid spar-type floating platform which has a lower part of the concrete and upper part of the steel.

Table A- 6 Sakiyama Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2013	Haenkaze, Toda Hybrid spar	Toda	Hitachi 2 MW downwind	Spread mooring system	100 meters (328 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Sakiyama, Fukue Island, Japan	5 kilometers (3.1 miles)	Goto Floating Wind Power LLC	Prototype demo	Operational (relocated from Kabashima in 2015)	
Fabrication & Installation					
Hull	**Mooring and Anchor**	**Power Cable**	The hybrid hull was dry towed by a barge to the assembly site at Kabashima. The hull was lifted by a crane and floated on the sea. The tower, nacelle, and rotor were installed on top of the hull. The assembled floating offshore wind turbine was towed to the offshore site for installation. The mooring and dynamic cable were connected to the hull at the site.		
Steel upper hull was connected with the concrete lower hull at the quay.	Three-point catenary mooring system (Steel chains)	The power generated is sent through 5 kilometers submarine cable and distributed to households via a substation.			
Site Condition			**Estimated Cost**		
Annual average wind speed 7.0 m/s, 50-year significant wave height 12.1 meters 50-year wind speed 45.8 m/s			N/A		

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FUKUSHIMA FORWARD PROJECT

Detailed information on the "Fukushima FORWARD" project is summarized in Table A-7.

The project has the world's first and only floating substructure.

The 14 MW Fukushima FOWF demonstration project (Fukushima FORWARD) is the world's first FOWF. It consists of three FOWTs of 2 MW, 5 MW, 7 MW and one 66 kV, 25 MVA floating substation. The floating substation includes 66 kV and 22 kV switchgear. The 22 kV voltage produced by the wind turbine is stepped up to 66 kV by the substation and transmitted to the surface using 66 kV submarine cables. This is the world's first 66 kV floating substation and dynamic export cable.

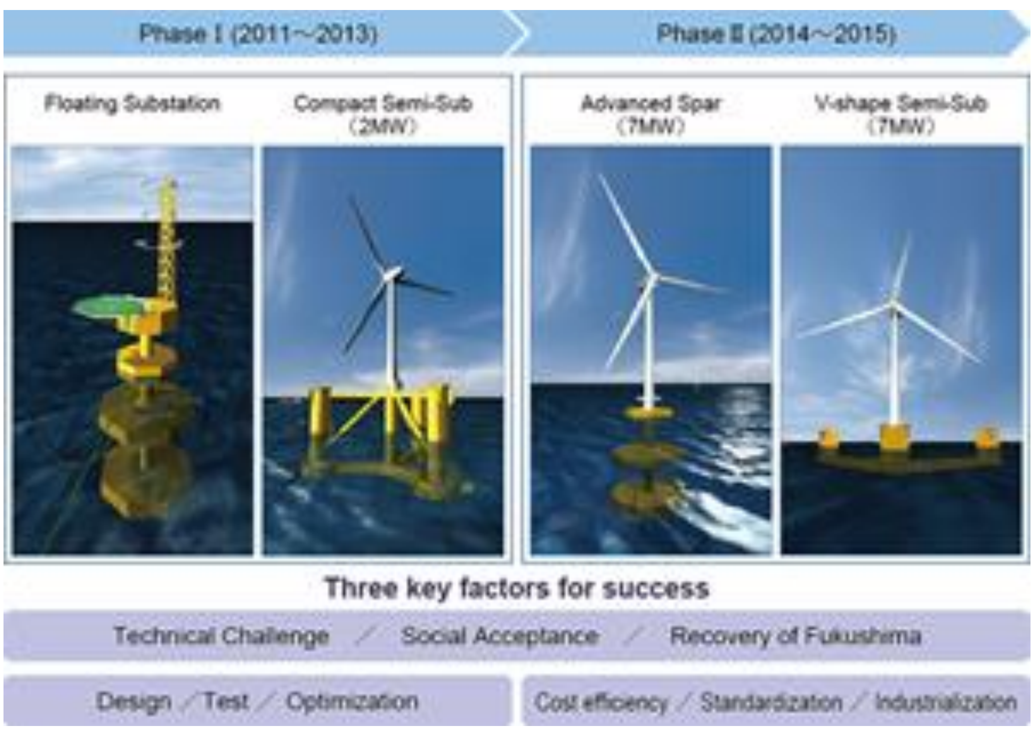

Figure A-5 Fukushima FORWARD Project

Table A-7 Fukushima FORWARD Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2013 (Phase 1)	Fukushima Kizuna, Advanced Spar	Japan Marine United Corporation (JMU)	66kV, 25MVA Floating Substation	Spread mooring system, 4 line catenary	120 meters (394 feet)
2013 (Phase 1)	Fukushima Mira, compact semi-submersible	Mitsui Engineering & Shipbuilding Co., Ltd. (MES)	Hitachi 2 MW downwind	Spread mooring system, 6 line catenary	122-123 meters (400-403 feet)
2015 (Phase 2)	Fukushima Shimpuu, V-shape Semi-Submersible	Mitsubishi Heavy industries, Ltd. (MHI)	MHI 7 MW	Spread mooring system, 8 line catenary	125 meters (410 feet)
2016 (Phase 2)	Fukushima Hamakaze, Advanced Spar	Japan Marine United Corporation (JMU)	Hitachi 5 MW downwind	Spread mooring system, 6 line catenary	110-120 meters (361-394 feet)

Location	Distance To Shore	Developer	Development Stage	Status
Offshore Fukushima, Japan	23 kilometers (14.3 miles)	Fukushima Offshore Wind Consortium	Prototype demo	Operational, 7 MW Fukushima Shimpuu is being dismantled.

Fabrication & Installation

Hull	Mooring And Anchor	Power Cable	
Advanced spar hulls were manufactured by JMU. The compact semi-submersible was manufactured by MES. V-shape semi-submersible was manufactured by MHI.	All mooring chains used for the four floaters, the material of which is made by Nippon Steel & Sumitomo Metal, are produced at the Hamanaka factory. Anchors used are Vryhof drag embedment anchors for floating substation, 2 MW and 7 MW floating offshore wind turbines.	Furukawa Electric provided 22 kV inter-array and 66 kV export submarine cables. First Subsea supplied cable connectors.	In Phase 1, the 2 MW wind turbine for the compact semi-submersible was installed on the hull at MES then was towed to Onahama port in Fukushima prefecture. The advanced spar for the floating substation left Isogo dock of JMU and towed to the installation site directly. In Phase 2, the 7 MW wind turbine for V-shaped semi-submersible was installed on the hulls at Onahama port. The 5 MW Wind turbine for the advanced spar was installed on the hulls in the port of Sumoto, Japan. The assembled floating offshore wind turbines were towed to the offshore site for installation. The anchors and mooring chains were pre-laid at the offshore site. The floating offshore wind turbines were hooked-up to the mooring system after tow out. The export cable and floating substation were installed in Phase 1. After export cables were installed, the dynamic cables were installed and hooked up to the hulls.

Site Condition	Estimated Cost
Annual mean wind speed around 7.5 m/s, Annual mean significant wave height around 1.6 meters 50-year wind speed 48.3 m/s, 50-year significant wave height 11.71 meters	JPY 18.8 billion (US$157 million)

Fukushima FORWARD Project

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SEATWIRL S1 PROJECT

Detailed information on the "SeaTwirl S1" project is summarized in Table A-8. SeaTwirl S1 is the world's first floating vertical axis wind turbine connected to the grid.

Figure A- 6 SeaTwirl S1 Projec

The 30 kW SeaTwirl S1 floating offshore wind turbine is the world's first floating vertical axis wind turbine connected to the grid.

The wind turbine, the tower, and the sub-sea part are assembled and rotate as one unit. Around the tower, above the water surface but below the wind turbine, is an enclosed, stored generator housing that is static or non-rotating. The generator housing and the wind turbine are anchored safely to the seabed by several catenary mooring lines.

Table A-8 SeaTwirl S1 Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2015	SeaTwirl Spar	SeaTwirl	30 kW Vertical Axis Wind Turbine	Spread mooring system	35 meters (115 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Lysekil, Sweden	N/A	SeaTwirl	Small Scale prototype demo	Operational	
Fabrication & Installation					
Hull	**Mooring and Anchor**	**Power Cable**	N/A		
N/A	Three point mooring	connected to grid			
Site Condition			**Estimated Cost**		
Experienced winds of up to 35 m/s			N/A		

SeaTwirl S1 Project

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HYWIND SCOTLAND PROJECT

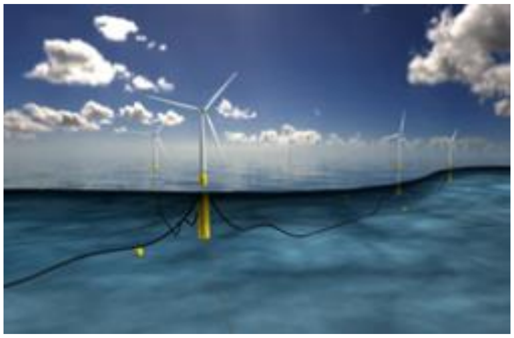

Figure A-7 Hywind Scotland pilot park

Detailed information on the "Hywind Scotland" project is summarized in Table A-9. Hywind Scotland is the world's first FOWF. The 30 MW Hywind Scotland pilot park in UK North Sea was the world's first floating wind farm. The wind farm has been producing since 2017, demonstrating the feasibility of floating wind farms that could be ten times larger.

The pilot park covers around 4 square kilometers (1.5 square miles) and is the current largest FOWF in the world. The 1MW/1.3MWh 'Batwind' battery equipped intelligent software, is paired with the wind farm, which adds the world first energy storage capabilities to the world's first floating wind farm.

Table A-9 Hywind Scotland Project - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2017</td><td>Hywind Spar</td><td>Equinor</td><td>Siemens 5×6 MW</td><td>Spread mooring system</td><td>95-120 meters (312-394 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Peterhead, Scotland, UK</td><td>25 kilometers (15.5 miles)</td><td>Hywind (Scotland) Limited</td><td>Pre-commercial</td><td colspan="2">Operational</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">The substructures were transported in a horizontal position to the onshore assembly site at Stord on the west coast of Norway. Then they were filled with close to 8,000 tons of seawater to make them stay upright. Finally, they were filled with around 5,500 tons of solid ballast while pumping out approximately 5,000 tons of seawater to maintain draft.
Tower, nacelle, and rotor were fully assembled onshore. Onshore assembly reduces the time and risk of offshore operations. The semi-submersible crane vessel Saipem 7000 lifted and mated the pre-assembled turbines to the verticalized spar-type substructure in the fjord off Leirvik on Stord. The floating wind turbines were then pre-tested before towed to the offshore site for installation. Technip was contracted for towing, mooring operations, and connection of the floating wind turbines offshore Scotland.</td></tr>
<tr><td>Updated design from the Hywind Demo,
Steel hull was constructed by Navantia-Windar at the Navantia Fene Yard in Spain and transported by Technip and installed offshore Scotland.</td><td>3-line catenary mooring system (chain),
Isleburn supplied 15 suction anchors.</td><td>Nexans supplied 13.6 kilometers (8.5 miles) of dynamic cables, 30 kilometers (18.6 miles) of export cables, and associated accessories with a transmission voltage of 33 kV.
Subsea 7 installed the export cable and 4 dynamic array cables.</td></tr>
</table>

Site Condition	Estimated Cost
The average wind speed in this area of the North Sea is around 10 m/s, while the average wave height is 1.8 meters. Experienced a severe winter storm with wave heights up to 8.2 meters (27 feet).	Around NOK 2 billion (~US$210 million), realizing a 60-70 percent cost reduction per MW from the Hywind demo project in Norway

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FLOATGEN PROJECT

Figure A-8 Floatgen Project

Detailed information on the "Floatgen" project is summarized in Table A-10. Floatgen is France's first offshore wind turbine. It is the world's first barge-type FOWT.

Floatgen is a 2MW floating wind turbine demonstrator installed at the testing site SEM-REV. The project is a joint venture of Ideol, Bouygues Travaux Publics, Centrale Nantes engineering school, RSK Group, Zabala, the University of Stuttgart, and Fraunhofer IWES. SEM-REV is the first European site for multi-technology offshore testing that is connected to the grid.

Table A-10 Floatgen Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2018	Ideol Damping Pool, barge	Ideol	Vestas 2 MW	Spread mooring system	33 meters (108 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Le Croisic, France	20 kilometers (12.4 miles)	Floatgen Consortium	Prototype demo	Operational	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	Hydro Group and regional partner Wenex Equipements developed and provided equipment for the installation, including connectors, hub, dynamic cable, and cable hang-off. The mooring was pre-installed by Bourbon as the construction of the concrete floating foundation built by Bouygues Travaux Publics in Saint-Nazaire was coming to an end. At the conclusion of the hull construction phase, the wind turbine was fixed into position, quayside, on the hull. The whole assembly weas subsequently towed out from the Le Croisic coast to the installation site, SEM-REV. JIFMAR executed the hook-up to the mooring lines, which had been pre-laid in July 2017. The turbine was connected to export cable and Floatgen became fully operational on Tuesday 18 September.		
Concrete hulls were constructed by Bouygues Travaux Publics.	Mooring system consists of 6 synthetic fiber (nylon) mooring lines, a consortium led by Le Béon Manufacturing supplied the mooring system. Drag embedded anchors were supplied by Mooreast.	The SEM-REV installation is capable of connecting any device cable to the export cable with a 24kV voltage connector. A 1300-meter-long umbilical (including a dynamic section of 580 meters) was constructed by Hydro Group.			
Site Condition			**Estimated Cost**		
Produced power up to 5.5 meters of significant wave height and up to 24.2 m/s of wind speed Experienced maximum wave heights of up to 12.5 meters (significant waves of up to 6.5 meters) Maximum wave height (Hmax) at the site is 16 meters			EUR 20 million (US$22.5 million)		

Floatgen Project

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HIBIKI PROJECT

Figure A- 9 Hibiki Project

Detailed information on the "Hibiki" project is summarized in Table A-11. The Hibiki is Japan's first barge-type FOWT.

The 3 MW Hibiki was developed by Japanese NEDO (New Energy and Industrial Technology Development Organization) and its Consortium group (Marubeni, Hitz, Glocal, Eco Power, Tokyo University, Kyuden Mirai Energy). The turbine is a compact 2-blade upwind type. The barge-type floating substructure is made of steel.

Table A-11 Hibiki Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2019	Ideol Damping Pool, barge	Ideol	Aerodyn SCD 3 MW, 2 bladed	Spread mooring system	55 meters (180 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Kitakyushu, Japan	15 kilometers (9.3 miles)	NEDO	Prototype demo	Operational	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	The hull was built at Hitachi Zosen's Sakai shipyard and towed to the Kitakyushu Port. Then, the tower and wind turbine were installed on the hull at Kitakyushu port. The floating wind turbine was towed to the offshore installation site, where it was connected to the mooring system and the grid via power cables.		
Hitachi Zosen Co., Ltd. designed and manufactured hull.	Mooring and anchoring system consist of a total of 9 studless chains and ultra-high holding power anchors.	N/A			
Site Condition			**Estimated Cost**		
Typhoon-prone area Faced three super-typhoons just after the installation			N/A		

Hibiki Project

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W2POWER 1:6 SCALE PROJECT

Figure A- 10 The W2Power 1:6 prototype

Detailed information on the "W2Power 1:6 Scale" project is summarized in Table A-12. The "W2Power 1:6 Scale" is Spain's first floating offshore wind platform.

The W2Power 1:6 prototype is Spain's first floating offshore wind platform. It was tested at the PLOCAN test site off Gran Canaria between June and October 2019 with an aim to collect information from different parameters that will allow further development and optimization of this multi-turbine platform. This test was carried out within the framework of the WIP10 + project (Wind Integrated Platform for 10+ MW Power Per Foundation).

Table A-12 W2Power 1:6 Scale Project - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2019</td><td>EnerOcean W2Power semi-submersible</td><td>EnerOcean</td><td>2×100 kW twin-rotor</td><td>Single point mooring</td><td></td></tr>
<tr><th>Location</th><th>Distance to Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Gran Canaria, Spain</td><td>N/A</td><td>N/A</td><td>Small scale prototype demo</td><td colspan="2">Decommissioned in 2019</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring and Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">N/A</td></tr>
<tr><td>W2Power, built and assembled at the Astican Shipyard</td><td>N/A</td><td>This PLOCAN test site is operative for grid and non-grid connected prototypes.
Grid connection: 2 cables x 5 MW</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">N/A</td><td colspan="3">N/A</td></tr>
</table>

<u>W2Power 1:6 Scale Project</u>

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WINDFLOAT ATLANTIC (WFA) PROJECT

Detailed information on the "WindFloat Atlantic (WFA)" project is summarized in Table A-13. The project features the world's first application of innovative 66 kV technology to dynamic cabling for FOWF.

Figure A-11 The 25 MW WindFloat Atlantic Project

The 25 MW WindFloat Atlantic (WFA) project is developed by the Windplus consortium comprising EDP Renewables, Engie, Repsol, and Principle Power. The WFA is the world's second FOWF. The FOWTs are the world's largest floating wind turbines. The project has used the first ever Lankhorst Gama98 Dyneema DM20 mooring ropes. The project features the world's first application of innovative 66 kV technology to dynamic cabling for FOWF.

Table A-13 WindFloat Atlantic (WFA) Project - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2020</td><td>WindFloat semi-submersible</td><td>Principle Power</td><td>MHI Vestas 3×8.4 MW</td><td>Spread mooring system</td><td>85-100 meters (279-328 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Viana do Castelo, Portugal</td><td>20 kilometers (12.4 miles)</td><td>Windplus consortium</td><td>Pre-commercial</td><td colspan="2">Operational</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">Portuguese transmission company REN subcontractor Hengtong constructed and installed an 18kilometers, 150kV export cable. The fabrication and load out of the first WindFloat (WFA-3) was completed in Fene (Spain) and the platform was dry towed, floated-off and then moored to the quayside in the port of Ferrol for the full assembly of the tower and the wind turbine. The FOWT was then towed to the offshore site for installation.

The other two WindFloat hulls (WFA-1, WFA-2) were towed to the port of Ferrol for a full assembly of the tower and the wind turbine before tow to the offshore site. Bourbon Subsea Services was contracted for the offshore installation. The mooring systems were pre-laid in the first phase. The wind turbines were towed to the offshore site and hooked up in a second phase, which also includes the installation and hook up of the inter-array electrical cables.</td></tr>
<tr><td>Two of them were manufactured by ASM Industries (Portugal), and the third at the Fene shipyard in Spain by Navantia-Windar (Spain).</td><td>Mooring systems of the turbines are made up of three catenary mooring lines of Gama98 rope construction made from Dyneema DM20 attached to chain and clump weight and drag embedded anchors by Vryhof.</td><td>The floating wind turbines are connected via a network of inter-array cables to one export cable. JDR Cable Systems supplied 66 kV dynamic array cables and designed a dynamic cable break away system.</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">N/A</td><td colspan="3">EUR 120 million (US$134)</td></tr>
</table>

WindFloat Atlantic (WFA) Project

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KINCARDINE PROJECT

Figure A-12 The 50 MW Kincardine

Detailed information on the "Kincardine" project is summarized in Table A-14.

The 50 MW Kincardine is being developed by Kincardine Offshore Wind (KOWL), a wholly owned subsidiary of Pilot Offshore Renewables (PORL), a joint venture between MacAskill Associates and Renewable Energy Ventures.

The wind farm covering 110 square kilometers (42.5 square miles) will be the world's largest FOWF upon completion. First power from the project was achieved by connecting 2MW to the British electricity grid in October 2018.

Table A-14 Kincardine Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2020	WindFloat semi-submersible	Principle Power	MHI Vestas 2 MW (former WF1), MHI Vestas 5×9.5 MW	Spread mooring system	60-80 meters (197-262 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Kincardineshire, Scotland, UK	15 kilometers (9.3 miles)	KOWL	Pre-commercial	WF1 relocated and operational in 2018, the five 9.5 MW turbines are under construction	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	Cobra Wind is responsible for the engineering, design, supply, construction, and commissioning of the Kincardine floating wind farm. Bourbon Subsea Services was contracted for turbine installation. Bourbon completed the installation of the 2 MW turbine at the Kincardine site in 2018, including towing the hull to Dundee, pre-laying the 4-leg mooring system, and installing the fully assembled wind turbine on site. Global Offshore installed one 18 kilometers export cable and completed the connection of the first 2MW turbine, of six, on the Kincardine site in 2018. Global Offshore will install one export and five inter array cables at the site, totaling 30.3 kilometers to connect the rest five turbines.		
One (former WF1) was supplied by Principle power, five hulls will be constructed by Navantia-Windar.	The mooring system is provided by Vryhof, which appointed Farinia Group for supplying the clump weights. UK contractor First Subsea was contracted to provide platform mooring connectors.	Prysmian Group was contracted by Cobra Wind to provide the inter-array as well as export cables, including two 33 kV export cables and 33 kV inter-array cables.			
Site Condition			**Estimated Cost**		
UK North Sea off the coast of Scotland			£350 million (US$445 million)		

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BLUESATH PROJECT

Figure A- 13 BlueSATH Project

Detailed information on the "BlueSATH" project is summarized in Table A-15.

BlueSATH is a FOWT deployment of a 1:6 scale prototype of a 10 MW wind turbine using SATH (Swinging Around Twin Hull) floating technology in open sea waters. It will be commissioned in 2020, and the aim is to model the behavior of SATH, allowing structural optimization, cost reduction, and validating structural turbine integrity.

The obtained results and findings will be applied in the 2 MW real-scale prototype DemoSATH to be installed on the Basque Marine Energy Platform (BIMEP) in 2021.

Table A-15 BlueSATH Project - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2020</td><td>Saitec SATH 1:6</td><td>Saitec</td><td>Aeolos 30 kW</td><td>Single point mooring system</td><td>N/A</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Santander, Spain</td><td>800 meters (2,625 feet)</td><td>Saitec</td><td>Small scale prototype demo</td><td colspan="2">Commissioning planned for 2020</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">75% of the subcontracting budget has been allocated to companies in the region and has counted with the participation of members of the Cluster Seas of Innovation Cantabria such as the Port of Santander, IHCantabria, Degima, Astander, and Acorde.
The BlueSATH was towed from Astander's Dock Pontejos towards its offshore site. Once at the location, the floating wind platform was hooked-up to the already-laid mooring lines.</td></tr>
<tr><td>The tubular hulls of BlueSATH are constructed from reinforced concrete with the remaining structure using steel.</td><td>Single point mooring, 3 x 150 meters (chain), drag anchor</td><td>N/A</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">The Abra del Sardinero has been selected due to its metoceanic conditions (wind, waves, currents, and depth) suitable to create a real scaled environment.</td><td colspan="3">EUR 2 million (US$2.2 million)</td></tr>
</table>

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TETRASPAR DEMO PROJECT

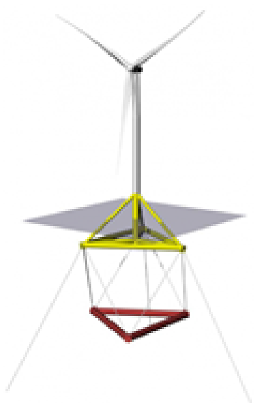

Figure A-14 TetraSpar Demo Project

Detailed information on the "TetraSpar Demo" project is summarized in Table A-16. Innogy, Shell and Stiesdal Offshore Technologies (SOT) have reached the final investment decision on floating wind demonstration project in Norway.

The project will feature SOT's TetraSpar floating foundation supporting a 3.6 MW Siemens Gamesa direct-drive turbine, which will be tested at the test site of the Marine Energy Test Centre (Metcentre) near Stavanger in 2020.

The Zefyros (former Hywind Demo) has been chosen as the connection point (hub) to the onshore grid.

Table A-16 TetraSpar Demo Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2020	Stiesdal TetraSpar, Spar	Stiesdal	Siemens Gamesa 3.6 MW	Spread mooring system	220 meters (722 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Karmøy, Norway	10 kilometers (6.2 miles)	Innogy, Shell and SOT	Prototype demo	Installation scheduled for 2020	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	The TetraSpar partners predict the concept will provide "leaner manufacturing, assembly, and installation processes with lower material costs" than other floating concepts. SOT's TetraSpar floating wind foundation is based on a modular layout, using a tubular steel main structure with a suspended keel. SOT will use industrialized manufacturing processes and pre-assembly efficiencies to reduce installation times. The entire plant is towed to the site using tugboats, avoiding higher-cost specialized vessels.		
Components for the prototype will be manufactured by Welcon in Give, Denmark, and will be transported to the Port of Grenaa to be assembled.	PRINCIPIA is in charge of the design verification of the mooring system and the floating foundation	SOT signed a supply contract with UNITECH Offshore AS for a dynamic power cable and grid connection			
Site Condition			**Estimated Cost**		
Near Zefyros (former Hywind Demo)			EUR 18 million (US$20.5 million)		

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DEMOSATH PROJECT

Figure A-15 DemoSATH Project

Detailed information on the "DemoSATH" project is summarized in Table A-17.

The project will test the very first full-scale floating wind turbine connected to the Spanish grid using SATH (Swinging Around Twin Hull) technology in the open sea test site Biscay Marine Energy Platform (BiMEP).

SATH technology is based on a twin hull made of modularly prefabricated and subsequently braced concrete elements. The hull can align itself around a single point of mooring according to the wind and wave direction. The technology stands out as the fourth concept using concrete around the world.

Table A-17 DemoSATH Project – Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2021</td><td>Saitec SATH</td><td>Saitec</td><td>2 MW</td><td>Single point mooring system</td><td>85 meters (279 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Basque, Spain</td><td>3.2 kilometers (2 miles)</td><td>Saitec</td><td>Prototype demo</td><td colspan="2">Marine operations are planned by the end of 2021</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">Marine operations are planned by the end of 2021.
The floating wind turbine will be assembled in the port of Bilbao, Spain. From there, it will be towed to its anchorage point in BiMEP.</td></tr>
<tr><td>Concrete twin hull with heave plate, Saitec Offshore Technologies will be responsible for the design and project management during the project's duration.</td><td>Single point mooring,
Drag anchors</td><td>At BiMEP test site, each berth is connected to the onshore substation via a dedicated three-phase submarine cable in series with a land three-phase line, both at 13.2 kV.</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">Operation significant wave height 2.8 m, wind speed 12 m/s
50-year storm significant wave height 10.2 m,
50-year wind speed 20 m/s</td><td colspan="3">EUR 15.5 million (US$17.3 million)</td></tr>
</table>

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EOLMED PROJECT

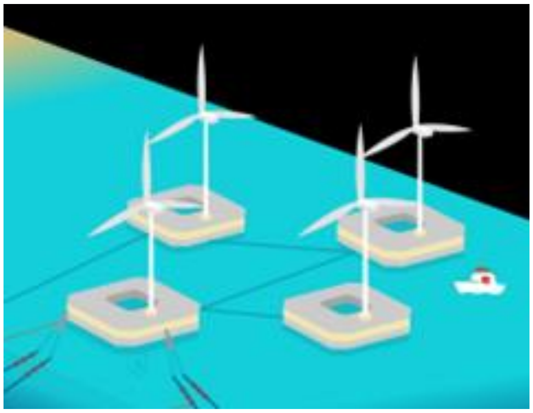

Figure A-16 EolMed Project

Detailed information on the "EolMed" project is summarized in Table A-18.

The 25 MW floating wind farm is under development by Eolmed, a consortium led by the French renewable energy developer Quadran Energies Marines and includes Ideol, the civil engineering leader Bouygues Travaux Publics and the wind turbine manufacturer Senvion.

The pilot project will be France's first floating pilot wind farm in the French Mediterranean Sea.

Table A-18 EolMed Project – Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2021	Ideol Damping Pool, barge	Ideol	Senvion 4×6.2 MW	Spread mooring system	55 meters (180 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Gruissan, Mediterranean Sea, France	15 kilometers (9.3 miles)	EolMed	Pre-commercial	Expected operating by late 2020/early 2021	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	Quadran is responsible for operation. Ideol and its partner are responsible for offshore installation. Senvion is responsible for turbine/floater integration, turbine commissioning, and maintenance.		
Ideol and its partner Bouygues Travaux Publics are responsible for design and construction of the concrete hull.	6 mooring lines made of synthetic ropes, and drag anchors.	Quadran is responsible for 33 kV export cable and connection to the grid. Ideol and its partner are responsible for 33 kV inter-array cables.			
Site Condition			**Estimated Cost**		
Mediterranean Sea			EUR 215 million (US$236.2 million)		

EolMed Project

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PROVENCE GRAND LARGE (PGL) PROJECT

Figure A-17 Provence Grand Large (PGL) Project

Detailed information on the "Provence Grand Large (PGL)" project is summarized in Table A-19.

The 25MW floating offshore wind farm, owned by EDF Energies, will be the world's FOWF with TLP (Tension Leg Platform)-type floating substructures.

The floating substructure is modularized, which does not require construction or port infrastructure. Dynamic inter-array cable connecting the wind turbines will be 66 kV.

Table A-19 Provence Grand Large (PGL) Project - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2021</td><td>SBM TLP</td><td>SBM Offshore</td><td>Siemens Gamesa 3×8.4 MW</td><td>Tension leg</td><td>100 meters (328 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Napoleon beach, Mediterranean Sea, France</td><td>17 kilometers (10.6 miles)</td><td>EDF Energies</td><td>Pre-commercial</td><td colspan="2">Expected to be commissioned in 2021</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">Before being transported to sea, the hulls will be built, and the wind turbines assembled at the Gloria wharf. The site has a large land and is equipped with a wharf already developed and usable. Its draught allows the hull to be assembled and released into the water; the wind turbine will then be installed on top of the hull. The wharf is also away from the main marine traffic, thus limiting interference.
The FOWT will be towed to the offshore site to connect the anchor lines and dynamic cables.</td></tr>
<tr><td>Modularized hulls will be developed by SBM Offshore and IFP Energies Nouvelles (IFPEN).</td><td>Stretched anchor lines with suction anchors</td><td>Prysmian will supply 3 kilometers of 66 kV inter-array cables, 19 kilometers of export cables and onshore cables for a 9 kilometers route.</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">Mediterranean Sea</td><td colspan="3">EUR 200 million (US$225 million)</td></tr>
</table>

Provence Grand Large (PGL) Project

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NEW ENGLAND AQUA VENTUS I PROJECT

Figure A-18 New England Aqua Ventus I Project

Detailed information on the "New England Aqua Ventus I" project is summarized in Table A-20

The New England Aqua Ventus I is an up to 12 MW floating offshore wind pilot project to develop a renewable energy source off Maine's shores. The project is led by New England Aqua Ventus, LLC (NEAV), a joint venture between Diamond Offshore Wind and RWE Renewables.

This demonstration project will deploy a 10–12 MW turbine on VolturnUS, the floating concrete semi-submersible hull designed by the University of Maine.

Table A-20 New England Aqua Ventus I Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2023	VolturnUS, semi-submersible	University of Maine	12 MW	Spread mooring system	100 meters (328 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Monhegan Island in the Gulf of Maine, US	4.8 kilometers (3 miles)	New England Aqua Ventus, LLC (NEAV)	Prototype demo	Expected to be completed in 2023	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	Hull components will be transported by barge down the Penobscot River to Searsport, where they will be con-joined with the turbine and tower and subsequently towed to the UMaine Deepwater Offshore Wind Test Site at Monhegan Island. Upon arrival at the offshore site, the unit will be hooked to preinstalled chain moorings connected to preset drag anchors.		
Maine-based Cianbro will construct the modular platform segments at an existing industrial facility adjacent to the Penobscot River in Brewer.	Three catenary chain moorings anchored to the seabed with drag embedment anchors	An alternate current (AC) cable will join the turbine, and then connect to a 34.5 kilovolt (kV) subsea power cable extending from the test site to an onshore transition point.			
Site Condition			**Estimated Cost**		
Operational significant wave height 0-6 meters 50-year significant wave height 10.2 meters 50-year 10 mins wind speed at hub height 40 m/s 500-year significant wave height 12 meters 500-year 10 mins wind speed at hub height 45 m/s			US$100 million		

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HWIND TAMPEN PROJECT

Figure A-19 Hywind Tampen Project

Detailed information on the "Hywind Tampen" project is summarized in Table A-21

Hywind Tampen is an 88 MW floating wind project intended to provide electricity for the Snorre and Gullfaks offshore field operations in the Norwegian North Sea. It will be the world's first FOWF to power offshore oil and gas platforms.

It will also be the world's largest FOWF and an essential step in industrializing solutions and reducing costs for future offshore wind power projects by new installation techniques, concrete substructures, and a shared mooring design.

Table A-21 Hywind Tampen Project Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2022</td><td>Hywind Spar</td><td>Equinor</td><td>Siemens Gamesa 11×8 MW</td><td>Spread mooring system</td><td>260-300 meters (853-984 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Snorre and Gullfaks offshore fields, offshore Norway</td><td>140 kilometers (87 miles)</td><td>Equinor</td><td>Pre-commercial</td><td colspan="2">Scheduled to be commissioned in late 2022</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">Kvaerner with DOF Subsea will deliver marine operations for the project.
The marine operations part of the contract involves full project management, engineering, assembly site management, mooring system installation, units tow-to-field, and installation of the floating wind turbine units at the Tampen area. The Gulen Industrial Harbor will provide onshore and inshore areas for storage, assembly, and commissioning of all the components for the turbines, as well as necessary infrastructure and facilities in the project period. The wind turbines will be installed on top of the concrete hulls at Gulen Industrihamn in western Norway. The partners will use a land-based ring crane to perform turbine installation. Subsea 7 Norway AS will be responsible for the installation of electrical cables and connection to the Snorre and Gullfaks platform.</td></tr>
<tr><td>Floating concrete hull will be designed and constructed by Kvaerner. The 11 concrete hulls will be constructed at its facility at Stord in Norway, and then tow the bottom structures to the site at Dommersnes in the Vindafjord, where the construction will be completed.</td><td>Three-line mooring system A simplified mooring system which uses shared suction anchors, reducing the number of anchors from 33 to 19. Shared anchors supplied by Kvaerner Scana Offshore will deliver 33 hull brackets, used to attach anchoring lines to the hulls.</td><td>JDR will design and manufacture eleven 2.5 kilometers (1.6 mile)-long 66 kV dynamic inter-array cables and two 12.9 kilometers (8 miles) and 16 kilometers (10 miles) static export cables, each equipped with a JDR-designed breakaway system and a range of cable accessories.</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">Mean significant wave height of 2.8 meters</td><td colspan="3">A total of almost NOK 5 billion (US$545 million)
Equinor aims to reduce the cost of Hywind Tampen by 40% compared with Hywind Scotland</td></tr>
</table>

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GOLFE DU LION (EFGL) PROJECT

Detailed information on the "Golfe du Lion (EFGL)" project is summarized in Table A-22.

Figure A-20 Golfe du Lion (EFGL) Project

The 30 MW floating pilot project is being developed by Eoliennes Flottantes du Golfe du Lion (EFGL), a consortium comprising Engie, EDP Renewables, and Caisse des Dépôts. It is scheduled to deploy three V164-10.0 MW turbines sitting atop the semi-submersible WindFloat. Once installed, EFGL will feature the world's most powerful wind turbines in commercial operation, a landmark achievement for the floating offshore wind market.

Table A-22 Golfe du Lion (EFGL) Project - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2022</td><td>WindFloat semi-submersible</td><td>Principle Power</td><td>MHI Vestas 3×10 MW</td><td>Spread mooring system</td><td>65-80 meters (213-262 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Leucate-Le Barcarès, Mediterranean Sea, France</td><td>16 kilometers (9.9 miles)</td><td>EFGL</td><td>Pre-commercial</td><td colspan="2">Commissioning scheduled for 2022</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">ENGIE, EDPR and The Bank of Territories (Caisse des Depots Group) are experienced partners in renewable marine energy and major shipyards.
Eiffage provides strong internal know-how and availability of its yard of Fos/Mer with assembly locally.
Port-La Nouvelle will be the industrial and logistical base of the project.</td></tr>
<tr><td>3 hulls designed by Principle Power and built by Eiffage at yard of Fos/Mer.</td><td>Three anchor lines per float, with a maximum length of 600 m. Anchors may be conventional drag embedded anchors (DEA) with a mass of 15 t is the most suitable for the project.</td><td>RTE will create a connection of the export cable to the electrical substation.
Inter-array cables will be at a voltage of 66 kV.</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">Mediterranean Sea</td><td colspan="3">EUR 200 million (US$225 million)</td></tr>
</table>

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GROIX & BELLE-ILE PROJECT

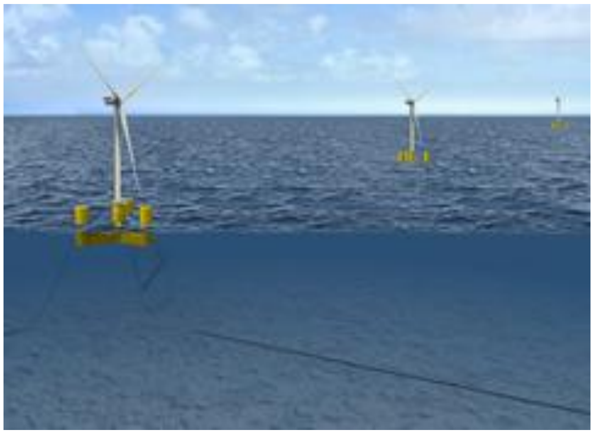

Figure A-21 Groix & Belle-Ile Project

Detailed information on the "Groix & Belle-Ile" project is summarized in Table A-23

The 28.5 MW Groix & Belle-Ile floating wind farm project will be developed, built and run by the company "Ferme Eolienne Flottante de Groix & Belle-Ile" (FEFGBI), company owned by a consortium made up of EOLFI, CGN Europe Energy, and the Banque des Territoires.

This will be the first FOWF offshore France in Atlantic Ocean.

Table A-23 Groix & Belle-Ile Project - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2022</td><td>Sea Reed semi-submersible</td><td>Naval Energies</td><td>MHI Vestas 3×9.5 MW</td><td>Spread mooring system</td><td>60 meters (197 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Brittany, France</td><td>22 kilometers (13.7 miles)</td><td>FEFGBI</td><td>Pre-commercial</td><td colspan="2">Commissioning scheduled for 2022</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">The floating wind turbines will be assembled in Brittany in existing and/or in-progress infrastructure in the port of Brest. They will then be towed one by one to the Groix & Belle-Ile site, secured using steel anchors and anchoring lines, and interconnected electrically. RTE, France's transmission system operator, will handle connecting the offshore pilot farm to the onshore electricity grid</td></tr>
<tr><td>Hybrid hull (steel & concrete) is developed by Naval Energies comprises four cylindrical steel columns and a concrete baseplate</td><td>The hull is anchored to the seabed with five anchor lines.</td><td>The Groix & Belle-Île floating wind site will be connected to the public electricity transmission network by underwater and underground connections.</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">Atlantic Ocean off the coast of France</td><td colspan="3">EUR 230 million (US$254 million)</td></tr>
</table>

Groix & Belle-Ile Project

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DONGHAE TWINWIND PROJECT

Figure A-22 Donghae TwinWind Project

Detailed information on the "Donghae TwinWind" project is summarized in Table A-24.

The 200 MW Donghae TwinWind will be built and operated by Shell and CoensHexicon. CoensHexicon, itself is a joint venture between Sweden-based Hexicon and local infrastructure group Coens Co.

The wind farm could be the first commercial floating wind farm

Table A-24 Donghae TwinWind Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2022	Hexicon multi-turbine semi-submersible	Hexicon	200 MW	Turret Mooring System	N/A
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Ulsan, Korea	62 kilometers (38.5 miles)	Shell and CoensHexicon	Commercial	Planning for deployment from 2022	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	N/A		
N/A	N/A	N/A			
Site Condition			**Estimated Cost**		
N/A			N/A		

Donghae TwinWind Project

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REDWOOD COAST PROJECT

Figure A-23 RedWood Coast Project

Detailed information on the "RedWood Coast" project is summarized in Table A-25

The Redwood Coast Energy Authority (RCEA), with support from a consortium of private companies, has submitted a lease application to the Bureau of Ocean Energy Management (BOEM) to advance the development of an offshore wind energy project off the coast of Humboldt County, in Northern California. The 100-150 megawatt (MW) FOWF is planned to be located more than 20 miles off the coast of Eureka, and could be California's first FOWT project.

Table A-25 RedWood Coast Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2024	WindFloat semi-submersible	Principle Power	100 – 150 MW	Spread mooring system	600-1,000 m (1,968-3,280 ft)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Humboldt County, California, US	40 kilometers (25 miles)	RCEA	Commercial	Expected to come online in 2024	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	The project partners plan for facilities at the Port of Humboldt Bay to potentially serve as the final assembly, hull load-out, turbine installation, and future maintenance base for WindFloat units. As a result, the Redwood Coast Project would require investment and revitalization of local infrastructure at the Port of Humboldt Bay and other nearby onshore facilities. RCEA and Project Partners currently assume an electrical system that involves connection of the Redwood Coast Project to the grid with one parallel 115 kV export cable from a floating substation moored at the site. This configuration will need to be compared to a configuration with two parallel cables of 66kV directly connected to an onshore transformer.		
WindFloat	The mooring system for each unit is made of conventional components: chain, polyester rope, and heavy chain connected to anchors.	Inter-array cables connecting turbines, Export cable to shore, Proposed interconnection at Humboldt Bay 115 kV substation.			
Site Condition			**Estimated Cost**		
Wind speed averages annually between 9 m/s and 10 m/s			N/A		

RedWood Coast Project

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CADEMO PROJECT

Figure A-24 CADEMO Project

Detailed information on the "CADEMO" project is summarized in Table A-26

The CADEMO (California Demonstration) project is a floating offshore wind renewable energy technology demonstration project. CADEMO is a 'pathfinder' project aimed at piloting the development, construction, installation, and operation of the first offshore wind project on the west coast of the US. The project aims to support the development of the local supply chain and skills to meet the opportunities of the newly emergent floating offshore wind industry.

Table A-26 CADEMO Project - Summary

Year	Floating Substructure Design, Type	Designer	Turbine, Power	Mooring System	Water Depth
2025	SBM TLP/ Saitec SATH	SBM Offshore/ Saitec	4×12 MW	Tension leg/ Single point mooring system	85-96 meters (279-315 feet)
Location	**Distance To Shore**	**Developer**	**Development Stage**	**Status**	
Offshore Vandenberg, California, US	4.8 kilometers (3 miles)	Cierco	Pre-commercial	Planning for operation by 2024/25	
Fabrication & Installation					
Hull	**Mooring And Anchor**	**Power Cable**	N/A		
The CADEMO project will introduce two new forms of hull specially designed to address the deep waters off the U.S. West Coast.	N/A	N/A			
Site Condition			**Estimated Cost**		
Average wind speed of 8.5 m/s			N/A		

CADEMO Project

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CASTLE WIND PROJECT

Detailed information on the "Castle Wind" project is summarized in Table A-27.

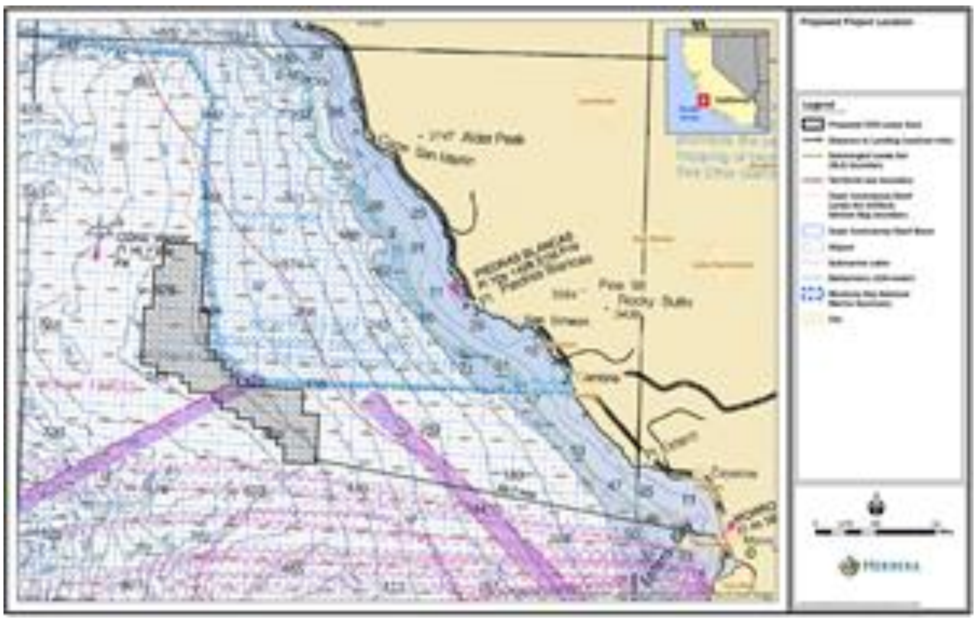

Figure A-25 Castle Wind Project

Castle Wind LLC has initiated development of a commercial scale offshore wind farm off the coast of Pt. Estero, California with a grid connection in Morro Bay.

The project is planned for a 1,000 MW net capacity. The final wind farm net capacity will be determined at a later date and will depend on the offshore site area, access to transmission capacity and market off-take demand.

Table A-27 Castle Wind Project - Summary

<table>
<tr><th>Year</th><th>Floating Substructure Design, Type</th><th>Designer</th><th>Turbine, Power</th><th>Mooring System</th><th>Water Depth</th></tr>
<tr><td>2026</td><td>N/A</td><td>N/A</td><td>1,000 MW</td><td>Spread mooring system</td><td>813-1,100 meters (2,665-3,608 feet)</td></tr>
<tr><th>Location</th><th>Distance To Shore</th><th>Developer</th><th>Development Stage</th><th colspan="2">Status</th></tr>
<tr><td>Offshore Morro Bay, California, US</td><td>48 kilometers (30 miles)</td><td>Castle Wind</td><td>Commercial</td><td colspan="2">Expected to come online in 2026</td></tr>
<tr><th colspan="6">Fabrication & Installation</th></tr>
<tr><th>Hull</th><th>Mooring And Anchor</th><th>Power Cable</th><td colspan="3" rowspan="2">Due to the size of the offshore wind components, fabrication of the FOWTs will take place at a ship building facility with adequate staging areas. The final assembly of the FOWTs will be done as close to the installation site as possible but will require a deepwater port. Due to the environmental and depth constraints, the Morro Bay harbor will not be suitable for the assembly of the FOWTs. The Morro Bay harbor will be used as a staging port for the project operation and maintenance.
Energy produced from all FOWTs is brought to an offshore, floating substation and delivered to shore via one or more (for redundancy purposes) export cable(s) using the same cable route and connecting to the Morro Bay substation.</td></tr>
<tr><td>Either the Hywind, or the WindFloat floating support structure, would be suitable for deployment in the Project.</td><td>Mooring lines will consist of chains, polyester lines, steel wires, shackles, fairleads and chain stoppers and conventional vertical load, drag embedded, or torpedo anchors.</td><td>Individual floating offshore wind turbines are electrically interconnected with inter-array cables to form an offshore wind farm.</td></tr>
<tr><th colspan="3">Site Condition</th><th colspan="3">Estimated Cost</th></tr>
<tr><td colspan="3">Average wind speed of 8.5 m/s</td><td colspan="3">N/A</td></tr>
</table>

Castle Wind Project

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Offshorewind. 2019. "Castle Wind Signs Deal for Future Project PPA". https://www.offshorewind.biz/2019/08/16/castle-wind-signs-deal-for-future-project-ppa/

APPENDIX C: SUMMARY OF ONGOING RESEARCH PROJECTS

Table A- 28 Ongoing Research Projects

Year	Project	Description/Technical Area	Investigator	Administrator
2015-2020	Efficient Multiline Mooring Systems for Floating Wind Turbines	This project seeks to develop a novel, integrated, and networked multiline mooring system for floating offshore wind turbines that can provide significant capital cost savings	Texas A&M University	NSF
2016-	MassCEC Metocean Data Initiative	In October 2016, MassCEC partnered with the Woods Hole Oceanographic Institution (WHOI) and AWS Truepower to install a vertical profiling WindCube LIDAR on the WHOI's Air-sea Interaction Tower (ASIT) located in state waters one mile south of Martha's Vineyard to collect wind data near federal offshore wind energy areas (WEAs).	Woods Hole Oceanographic Institution (WHOI) and AWS Truepower	Massachusetts Clean Energy Center (MassCEC)
2017-	Lidar Buoy Loan Program	In response to several inquiries and unsolicited proposals, DOE's Wind Energy Technologies Office has implemented a loan program to lend the buoys to qualified parties to acquire wind resource characterization data in areas of interest for offshore wind energy development. PNNL manages the loan program.	Pacific Northwest National Laboratory (PNNL)	DOE
2017-2021	Uncertainty Modeling, Probabilistic Models, and Life-cycle Reliability of Floating Offshore Wind Turbines	The project seeks to analyze floating offshore wind turbine uncertainties that arise due to the ocean environment and hydrodynamic calculations, as well as due to uncertainties in the structural and mechanical systems, which threaten the reliability and the feasibility of FOWTs.	Prairie View A&M University	NSF
2018-2021	Advanced Control Strategies for Floating Offshore Wind Farms	The primary goal of this project is to formulate, implement and quantify the performance of advanced floating wind offshore turbine farm control methodologies integrating multiple inputs and control actions through using comprehensive numerical simulations.	University of Maine	NSF

Year	Project	Description/Technical Area	Investigator	Administrator
2019-	Wake Modeling Challenge, Wake Effects and Wind Resource Wake Modeling Benchmarking	The aim of the project is to improve confidence in offshore wind wake models in the prediction of array efficiency, which is important to reduce uncertainty in energy yields for offshore wind farms.	No Data	Carbon Trust
2019-2023	IEA OC6	The Offshore Code Comparison, Collaboration, Continued, with Correlation and unCertainty (OC6) is an international research project run under the International Energy Agency (IEA) Wind Task 30. The project is focused on validating the tools used to design offshore wind systems.	National Renewable Energy Laboratory	IEA
2019-2021	Horizon 2020 SATH project	The aim of the SATH project is the demonstration in real conditions of a floating structure for offshore wind, which will allow a reduction in LCOE (Levelized Cost of Energy) over the current floating technology.	Saitec	EU
2019-2022	Horizon 2020 PivotBuoy project	The main project objective is to reduce the cost of energy (LCOE) of floating wind by 50% through the validation of the "PivotBuoy", an innovative subsystem that reduces the costs of mooring systems and floating platforms, allows faster and cheaper installation and a more reliable and sustainable operation.	X1 Wind (Exponential Renewables, S.L.)	EU
2019-2022	Horizon 2020 FLOTANT project	The main objective of FLOTANT project is to develop the conceptual and basic engineering, including performance tests of the mooring and anchoring systems and the dynamic cable to improve cost-efficiency, increased flexibility and robustness to a hybrid concrete-plastic floating structure	PLOCAN	EU
2019-2023	Horizon 2020 COREWIND project	The research team is developing two concrete-based floater concepts that include the required anchoring systems and cabling to enable the electricity to be delivered to the grid; aiming at making FOWTs cost-competitive.	The Catalonia Institute for Energy Research (IREC)	EU

Year	Project	Description/Technical Area	Investigator	Administrator
2019-2022	Horizon 2020 MooringSense project	Mooring systems are critical components in FOWTs, which are monitored through costly and unreliable load cells. The Mooring Sense project aims to develop an efficient risk-based integrity management strategy for mooring systems based on inexpensive and reliable online monitoring technology.	Centro Tecnologico Componentes (CTC)	EU
2019-2023	Horizon 2020 FLOAWER project	The FLOAting Wind Energy network (FLOAWER) will provide 13 Early Stage Researchers (ESR) with an interdisciplinary training with the aim to design better performing, economically viable floating wind turbines.	Centrale Nantes	EU
2019-2023	Horizon 2020 LIKE project	The LIKE project will train a new generation of scientists on emerging laser-based wind measurement techniques, and how these can find practical applications in the industry.	Technical University of Denmark (DTU)	EU
2019-2021	Horizon 2020 SeaTwirl project	SeaTwirl project introduces a novel solution with a smaller spar-buoy and uses the buoyant force of the ocean to support the weight of the turbine.	SeaTwirl AB	EU
2019-	Effect of Fatigue on the Capacity and Performance of Structural Concrete	Tufts University will quantify the effects of fatigue on the stiffness, strength, and durability of various marine concrete mixtures to facilitate the development of cost-effective, resilient concrete offshore wind support structures.	Tufts University	DOE
2019-	Coupled Aerodynamic and Hydrodynamic Hybrid Simulation of Floating Offshore Wind Turbines (FOWTs)	Oregon State University will use numerical models to simulate the combined effects of wind and waves on FOWTs in a wave basin.	Oregon State University	DOE
2019-	Advanced Next Generation High Efficiency Lightweight Wind Turbine Generator	American Superconductor Corporation of Ayer, Massachusetts will develop a high-efficiency lightweight wind turbine generator that incorporates high-temperature superconductor (HTS) materials to replace permanent magnets in the generator rotor, potentially reducing size and weight by 50%.	American Superconductor Corporation	DOE

Year	Project	Description/Technical Area	Investigator	Administrator
2019-	High Efficiency Ultra-Light Superconducting Generator for Offshore Wind	General Electric (GE) Research of Niskayuna, New York will develop a high-efficiency ultra-light low temperature superconducting (LTS) generator, leveraging innovations from GE's magnetic resonance imaging (MRI) business.	General Electric (GE)	DOE
2019-	Advanced Lightweight High Efficiency Permanent Magnet Direct Drive Generator for Wind Turbine Applications	WEG and partners will design, build and test an advanced permanent magnet direct drive lightweight generator that will be integrated into the existing WEG 4x platform to produce a more competitive product by significantly lowering system mass and cost while increasing energy capture.	WEG Electric Corporation (WEC)	DOE
2019-	On-Site Spiral Welding Enabling High Hub-Heights	Keystone Tower Systems will demonstrate on-site spiral welding of a 160-meter wind turbine tower, as well as installation of up-tower components with a tower-mounted self-hoisting crane.	Keystone Tower Systems, Inc.	DOE
2019-	Demonstrating a 10-12 MW Floating Wind Turbine by 2022	The University of Maine at Orono will develop an innovative floating platform that is low-cost, easy to manufacture, and capable of supporting a 10-12 MW wind turbine for a demonstration project planned for deployment off Monhegan Island, Maine.	University of Maine	DOE
2019-	Northern CA coast offshore wind feasibility study	The project will assess the environmental impacts, determine the required modifications of coastal infrastructure, examine stakeholder benefits and impacts, and evaluate local, state, and federal policies as they relate to offshore wind development.	Schatz Energy Research Center at Humboldt State University	Ocean Protection Council (OPC)
2019-	Energy Generation, Transmission, and Economic Viability Study	This study will evaluate wind patterns and associated energy generation profiles, estimate transmission upgrades, and assess the economic viability of three wind farm models.	Schatz Energy Research Center at Humboldt State University	Bureau of Ocean Energy Management (BOEM)

Year	Project	Description/Technical Area	Investigator	Administrator
2019-	Military mission compatibility, Geologic and seismic challenges, and environmental impacts of a subsea transmission cable study	This project will study military mission compatibility, geologic and seismic constraints, and the environmental impacts of subsea cabling.	Schatz Energy Research Center at Humboldt State University	California Governor's Office of Planning and Research
2020-2023	Novel and Efficient Seabed Ring Anchor for Omnidirectional Loading	This project will support a research team to develop models for the loading placed on multiline ring anchors subjected to wind, waves and other forces. A Multiline Ring Anchor (MRA) is a ring-shaped anchor designed to be deeply embedded in offshore soils for the purposes of anchoring multiple floating platforms.	University of California-Davis	NSF
2020	Floating Wind Joint Industry Project (JIP), Assessment of Wind Turbine Generators for floating wind farms	The project will build on previous Floating Wind JIP work that assessed FOWTs for floating wind, and additionally support FOWT suppliers, directly or indirectly, to investigate floating wind specific risks to their mechanical/electrical componentry.	Ramboll, MESH	Carbon Trust
2020	Floating Wind Joint Industry Project (JIP), Floating Wind Access and Availability	The accessibility and availability of bottom-fixed offshore windare relatively well known, however in FOWTs there is more uncertainty.	Seaspeed Marine Consulting, SeaRoc	Carbon Trust
2020	Floating Wind Joint Industry Project (JIP), Floating Wind Yield	The uncertainty in floating wind yield is primarily related to the additional degrees of freedom and quality of yield modeling that could impact yield, but also controller modifications, additional downtime, and sustained pitch during operation.	Frazer Nash Consultancy, National Renewable Energy Laboratory	Carbon Trust
2020	Floating Wind Joint Industry Project (JIP), Numerical Modeling Guidelines and Standards for Floating Wind	The project is to improve the understanding of guidance for the design of floating wind structures, including: defining the relevant load cases and guidance for an optimized outline design, a review of numerical modeling tools for floating wind turbine design, and a review of the leading standards and opportunities to harmonize.	Innosea, Sowento	Carbon Trust

Year	Project	Description/Technical Area	Investigator	Administrator
2020	Demonstration of Shallow-Water Mooring Components for FOWTs (ShallowFloat)	Floating Structure Mooring Concepts for Shallow and Deep Waters	Principle Power, Inc.	NOWRDC
2020	Design and Certification of Taut-synthetic Moorings for Floating Wind Turbines	Floating Structure Mooring Concepts for Shallow and Deep Waters	University of Maine	NOWRDC
2020	Dual-Functional Tuned Inerter Damper for Enhanced Semi-Sub Offshore Wind Turbine	Floating Structure Mooring Concepts for Shallow and Deep Waters	Virginia Tech University	NOWRDC
2020	Innovative Anchoring System for Floating Offshore Wind	Floating Structure Mooring Concepts for Shallow and Deep Waters	Triton Systems, Inc	NOWRDC
2020	Techno-Economic Mooring Configuration and Design for Floating Offshore Wind	Floating Structure Mooring Concepts for Shallow and Deep Waters	University of Massachusetts Amherst	NOWRDC
2020	Development of Advanced Methods for Evaluating Grid Stability Impacts	Power System Design and Innovation Challenge Statement	National Renewable Energy Laboratory	NOWRDC
2020	Development of a Metocean Reference Site near the Massachusetts and Rhode Island Wind Energy Areas	Development of a Metocean Reference Site	Woods Hole Oceanographic Institute	NOWRDC
2020	Enabling Condition Based Maintenance for Offshore Wind	Offshore Wind Digitization Through Advanced Analytics	General Electric	NOWRDC
2020	Physics Based Digital Twins for Optimal Asset Management	Offshore Wind Digitization Through Advanced Analytics	Tufts University	NOWRDC
2020	Radar Based Wake Optimization of Offshore Wind Farms	Offshore Wind Digitization Through Advanced Analytics	General Electric	NOWRDC
2020	Survival Modeling for Offshore Wind Prognostics	Offshore Wind Digitization Through Advanced Analytics	Tagup, Inc.	NOWRDC

Year	Project	Description/Technical Area	Investigator	Administrator
2020	20GW by 2035: Supply Chain Roadmap for Offshore Wind in the U.S.	Technology Solutions to Accelerate U.S. Supply Chain	National Renewable Energy Laboratory	NOWRDC
2020	ARCUS Vertical-Access Wind Turbine	Sandia National Laboratories will design a vertical-axis wind turbine (VAWT) system, ARCUS, with the goal of eliminating mass and associated cost not directly involved in capturing energy from the wind.	Sandia National Laboratories	DOE ARPA-e
2020	Design and Develop Optimized Controls for a Lightweight 12 MW Wind Turbine on an Actuated Tension Leg Platform	GE Research will design and develop optimized controls for a 12 MW (megawatt) FOWT. The team will use advanced control algorithms that operate the turbine and are designed concurrently with the integrated structure of the FOWT.	General Electric Company	DOE ARPA-e
2020	DIGIFLOAT: Development, Experimental Validation and Operation of a Digital Twin Model for Full-scale Floating Wind Turbines	Principle Power Inc. (PPI) plans to lead a consortium of public and private institutions to develop, validate, and operate the world's first digital twin software tailored to FOWT applications.	Principal Power Inc.	DOE ARPA-e
2020	A Low-Cost Floating Offshore Vertical Axis Wind System	The University of Texas at Dallas (UT-Dallas) team plans to develop a floating turbine design featuring a vertical axis wind turbine (VAWT).	The University of Texas at Dallas	DOE ARPA-e
2020	A Co-Simulation Platform for Off-Shore Wind Turbine Simulations	The University of Massachusetts Amherst will develop software for the coupled simulation and control co-design of FOWTs	The University of Massachusetts	DOE ARPA-e
2020	USFLOWT: Ultraflexible Smart Floating Offshore Wind Turbine	The National Renewable Energy Laboratory (NREL) will design an innovative system. The team's design, USFLOWT, is comprised of an advanced wind turbine with ultra-flexible and light blades, advanced aerodynamic control surfaces, and a revolutionary substructure: the SpiderFLOAT (SF).	National Renewable Energy Laboratory	DOE ARPA-e
2020	Wind Energy with Integrated Servo-control (WEIS): A Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems	The NREL will develop a Wind Energy with Integrated Servo-control (WEIS) model, a toolset that will enable control co-design (CCD) optimization of both conventional and innovative, cost-effective FOWTs.	National Renewable Energy Laboratory	DOE ARPA-e

Year	Project	Description/Technical Area	Investigator	Administrator
2020	The FOCAL Experimental Program	The NREL in collaboration with the University of Maine (UMaine) will develop and execute the Floating Offshore-wind and Controls Advanced Laboratory (FOCAL) experimental program.	National Renewable Energy Laboratory	DOE ARPA-e
2020	AIKIDO - Advanced Inertial and Kinetic energy recovery through Intelligent (co)-Design Optimization	Otherlab will develop a new architecture for wind systems based on compliant materials, energy-generating structural surfaces, and advanced control systems that overcome the need for stiff, expensive materials by actively controlling how the system interacts with the environment.	Otherlab – San Francisco	DOE ARPA-e
2020	Scale Model Experiments for Co-Designed FOWTs Supporting a High-Capacity (15MW) Turbine	WS Atkins will focus on generating experimental data that can be used to validate computer programs and new technologies developed for floating offshore wind turbine (FOWT) applications.	WS Atkins – Houston	DOE ARPA-e
2020	Computationally Efficient Atmospheric-Data-Driven Control Co-Design Optimization Framework with Mixed-Fidelity Fluid and Structure Analysis	Rutgers University will develop a computationally efficient, atmospheric-data-driven, control co-design optimization software framework for floating offshore wind turbine design. They will focus on developing a modular computational framework for the modeling, optimization, and control of primary structures coupled to the surrounding air, water, and actuator dynamics.	Rutgers University	DOE ARPA-e
2020	Model-Based Systems Engineering and Control Co-Design of Floating Offshore Wind Turbines	The University of Central Florida will develop a comprehensive causality-free modeling and simulation platform that facilitates control co-design, assists in incorporating multi-physics models, adapts to design changes, and allows rapid simulations to validate models and evaluate controllers.	The University of Central Florida	DOE ARPA-e
2020	Ultra-light Concrete Floating Offshore Wind Turbine with NASA-developed Response Mitigation Technology	The University of Maine (UMaine) team will design an ultra-lightweight, corrosion resistant, concrete FOWT equipped with NASA motion mitigation technology originally developed to reduce vibrations in rockets.	The University of Maine	DOE ARPA-e

Year	Project	Description/Technical Area	Investigator	Administrator
2020	On-site 3D Concrete Printing for Next Generation Low-Cost Wind Plants	The purpose of this agreement is to manufacture, demonstrate, and test wind tower sections and offshore wind energy components using an onsite three-dimensional concrete printed (3DCP) manufacturing process and design.	RCAM Technologies	California Energy Commission
2020	NextWind Real-time Monitoring System	The purpose of this project is to establish a digital foundation or digital twin, of a FOWT installation enabling continuous improvements in production optimization, lower levelized cost of energy and do so with a better understanding of the environmental impact and mitigations of these impacts.	Aker Solutions, Inc.	California Energy Commission
2020-2023	Horizon 2020 SEAFLOWER project	The objective of the project is to define a numerical procedure that can store the experience maturated in the oil and gas energy sector and the most recent research findings on anchor foundations to make them available to the needs of the offshore wind energy market.	University of Bologna	EU
2020-2024	Horizon 2020 STEP4WIND project	As a European Industrial Doctorate program, it will deliver 10 doctoral degrees supervised by three universities and five leading energy companies. The project will also develop specific tools and methods to address the technological and economic challenges of FOWTs.	Delft University of Technology (TU Delft)	EU
2020-	Optimizing Offshore Wind Farm Collector Networks	This research project looks into several stages of wind farm optimization on electrical infrastructure, including turbine placement, cable layout and selection and energy storage sizing and placement. The planned project output is a practical optimization tool that will be able to provide overall optimized wind farm designs.	University of Strathclyde	ORE Catapult
2020-	Regulatory Challenges for Delivering the Offshore Electrical Networks of the Future	This project sought to compare and contrast competing philosophies, including Offshore Transmission Owner (OFTO) regime and transmission system owner (TSO) regime and address the perceived strengths and weaknesses of each.	University of Strathclyde	ORE Catapult

Year	Project	Description/Technical Area	Investigator	Administrator
2020	Design, demonstrate, and validate a synthetic rope mooring for floating offshore wind turbines	The University of Maine will design, demonstrate, and validate a synthetic rope mooring for floating offshore wind turbines, which is expected to reduce the impact of offshore wind development on commercial fishing and reduce costs. The mooring system will be demonstrated on a full-scale floating offshore wind turbine as part of the New England Aqua Ventus I project.	University of Maine	DOE

Table A- 29 FOWTs – Summary of Ongoing Research Projects and Technical Challenge Areas

Category	Technical Challenge Area	Project	Investigator	Administrator
Turbine	Turbine design and optimization	Advanced Next Generation High Efficiency Lightweight Wind Turbine Generator	American Superconductor Corporation	DOE
	Turbine design and optimization	High Efficiency Ultra-Light Superconducting Generator for Offshore Wind	General Electric (GE)	DOE
	Turbine design and optimization	Advanced Lightweight High Efficiency Permanent Magnet Direct Drive Generator for Wind Turbine Applications	WEG Electric Corporation (WEC)	DOE
	Turbine design and optimization	Floating Wind Joint Industry Project (JIP), Assessment of Wind Turbine Generators for floating wind farms	Ramboll, MESH	Carbon Trust
	Turbine controller	Design and Develop Optimized Controls for a Lightweight 12 MW Wind Turbine on an Actuated Tension Leg Platform	General Electric Company	DOE ARPA-e
	Turbine controller	A Co-Simulation Platform for Off-Shore Wind Turbine Simulations	The University of Massachusetts	DOE ARPA-e
	Vertical axis wind turbines	ARCUS Vertical-Access Wind Turbine	Sandia National Laboratories	DOE ARPA-e

Category	Technical Challenge Area	Project	Investigator	Administrator
	Vertical axis wind turbines	A Low-Cost Floating Offshore Vertical Axis Wind System	The University of Texas at Dallas	DOE ARPA-e
	Design optimization	AIKIDO - Advanced Inertial and Kinetic energy recovery through Intelligent (co)-Design Optimization	Otherlab – San Francisco	DOE ARPA-e
Floating substructure	New design concept	Horizon 2020 COREWIND project	The Catalonia Institute for Energy Research (IREC)	EU
	New design concept	USFLOWT: Ultraflexible Smart Floating Offshore Wind Turbine	National Renewable Energy Laboratory	DOE ARPA-e
	New design concept	Horizon 2020 PivotBuoy project	X1 Wind (Exponential Renewables, S.L.)	EU
	New design concept	Horizon 2020 SATH project	Saitec	EU
	New design concept	Horizon 2020 SeaTwirl project	SeaTwirl AB	EU
	New material	Horizon 2020 FLOTANT project	PLOCAN	EU
	New material	Effect of Fatigue on the Capacity and Performance of Structural Concrete	Tufts University	DOE
	New material	Ultra-light Concrete Floating Offshore Wind Turbine with NASA-developed Response Mitigation Technology	The University of Maine	DOE ARPA-e
	Demonstration	Demonstrating a 10-12 MW Floating Wind Turbine by 2022	University of Maine	DOE
Mooring and Anchor	New material	Horizon 2020 FLOTANT project	PLOCAN	EU
	New configuration	Design and Certification of Taut-synthetic Moorings for Floating Wind Turbines	Principle Power, Inc.	NOWRDC
	New configuration	Dual-Functional Tuned Inerter Damper for Enhanced Semi-Sub Offshore Wind Turbine	University of Maine	NOWRDC
	New configuration	Innovative Anchoring System for Floating Offshore Wind	Virginia Tech University	NOWRDC

Category	Technical Challenge Area	Project	Investigator	Administrator
	New configuration	Techno-Economic Mooring Configuration and Design for Floating Offshore Wind	University of Massachusetts Amherst	NOWRDC
	New configuration	Design, demonstrate, and validate a synthetic rope mooring for floating offshore wind turbines	University of Maine	DOE
	New configuration	Efficient Multiline Mooring Systems for Floating Wind Turbines	Texas A&M University	NSF
	New configuration	Novel and Efficient Seabed Ring Anchor for Omnidirectional Loading	University of California-Davis	NSF
	New anchoring system design	Innovative Anchoring System for Floating Offshore Wind	Triton Systems, Inc	NOWRDC
	Mooring integrity	Horizon 2020 MooringSense project	Centro Tecnologico Componentes (CTC)	EU
Electrical Infrastructure	Dynamic power cable	Horizon 2020 COREWIND project	The Catalonia Institute for Energy Research (IREC)	EU
	Gird connection	Development of Advanced Methods for Evaluating Grid Stability Impacts	National Renewable Energy Laboratory	NOWRDC
	Transmission and interconnection	Energy Generation, Transmission, and Economic Viability Study	Schatz Energy Research Center at Humboldt State University	Bureau of Ocean Energy Management (BOEM)
	Layout optimization tool	Optimizing Offshore Wind Farm Collector Networks	University of Strathclyde	ORE Catapult
	Wind Farm Control	Advanced Control Strategies for Floating Offshore Wind Farms	University of Maine	NSF
	Regulatory Challenges	Regulatory Challenges for Delivering the Offshore Electrical Networks of the Future	University of Strathclyde	ORE Catapult
Construction (Manufacturing, Transportation, and Installation)	New method	On-site 3D Concrete Printing for Next Generation Low-Cost Wind Plants	RCAM Technologies	California Energy Commission

Category	Technical Challenge Area	Project	Investigator	Administrator
	New method	On-Site Spiral Welding Enabling High Hub-Heights	Keystone Tower Systems, Inc.	DOE
	Supply chain (US)	20GW by 2035: Supply Chain Roadmap for Offshore Wind in the U.S.	National Renewable Energy Laboratory	NOWRDC
	Coastal infrastructure (CA, US)	Northern CA coast offshore wind feasibility study	Schatz Energy Research Center at Humboldt State University	Ocean Protection Council (OPC)
Operation and Maintenance	Maintenance	Enabling Condition Based Maintenance for Offshore Wind	General Electric	NOWRDC
	Maintenance	Floating Wind Joint Industry Project (JIP), Floating Wind Access and Availability	Seaspeed Marine Consulting, SeaRoc	Carbon Trust
	Digital Twin	Physics Based Digital Twins for Optimal Asset Management	Tufts University	NOWRDC
	Digital Twin	DIGIFLOAT: Development, Experimental Validation and Operation of a DIGItal Twin Model for Full-scale Floating Wind Turbines	Principal Power Inc.	DOE ARPA-e
	Digital Twin	NextWind Real-time Monitoring System	Aker Solutions, Inc.	California Energy Commission
	Digitization	Radar Based Wake Optimization of Offshore Wind Farms	General Electric	NOWRDC
	Digitization	Survival Modeling for Offshore Wind Prognostics	Tagup, Inc.	NOWRDC
Site conditions	Metocean condition	Development of a Metocean Reference Site near the Massachusetts and Rhode Island Wind Energy Areas	Woods Hole Oceanographic Institute	NOWRDC
	Wind resource characterization	Lidar Buoy Loan Program	Pacific Northwest National Laboratory (PNNL)	DOE
	Wind resource characterization	MassCEC Metocean Data Initiative	Woods Hole Oceanographic Institution (WHOI) and AWS Truepower	MassCEC

Category	Technical Challenge Area	Project	Investigator	Administrator
	Geologic and seismic conditions	Military mission compatibility, Geologic and seismic challenges, and environmental impacts of a subsea transmission cable study	Schatz Energy Research Center at Humboldt State University	California Governor's Office of Planning and Research
	Annual Energy Production (AEP)	Floating Wind Joint Industry Project (JIP), Floating Wind Yield	Frazer Nash Consultancy, National Renewable Energy Laboratory	Carbon Trust
	Training and knowledge	Horizon 2020 LIKE project	Technical University of Denmark (DTU)	EU
Design Analysis Tool and Validation	Validation of tool	IEA OC6	National Renewable Energy Laboratory	IEA
	Validation of tool	Horizon 2020 FLOTANT project	PLOCAN	EU
	Validation of tool	Horizon 2020 COREWIND project	IREC	EU
	Validation of tool	Coupled Aerodynamic and Hydrodynamic Hybrid Simulation of Floating Offshore Wind Turbines (FOWTs)	Oregon State University	DOE
	Control co-design tool	Wind Energy with Integrated Servo-control (WEIS): A Toolset to Enable Controls Co-Design of Floating Offshore Wind Energy Systems	National Renewable Energy Laboratory	DOE ARPA-e
	Control co-design tool	Computationally Efficient Atmospheric-Data-Driven Control Co-Design Optimization Framework with Mixed-Fidelity Fluid and Structure Analysis	Rutgers University	DOE ARPA-e
	Control co-design tool	Model-Based Systems Engineering and Control Co-Design of Floating Offshore Wind Turbines	The University of Central Florida	DOE ARPA-e
	Model-scale experimental dataset	The FOCAL Experimental Program	National Renewable Energy Laboratory	DOE ARPA-e
	Model-scale experimental dataset	Scale Model Experiments for Co-Designed FOWTs Supporting a High-Capacity (15MW) Turbine	WS Atkins – Houston	DOE ARPA-e

Category	Technical Challenge Area	Project	Investigator	Administrator
	Wake modeling	Wake Modeling Challenge, Wake Effects and Wind Resource Wake Modeling Benchmarking	No Data	Carbon Trust
	Anchor design	Horizon 2020 SEAFLOWER project	University of Bologna	EU
	Tools and knowledge	Uncertainty Modeling, Probabilistic Models, and Life-cycle Reliability of Floating Offshore Wind Turbines	Prairie View A&M University	NSF
	Tools and knowledge	Horizon 2020 STEP4WIND project	Delft University of Technology (TU Delft)	EU
	Tools and knowledge	Horizon 2020 FLOAWER project	Centrale Nantes	EU
Design guidelines and standards	Literature review	Floating Wind Joint Industry Project (JIP), Numerical Modeling Guidelines and Standards for Floating Wind	Innosea, Sowento	Carbon Trust