FLOATING OFFSHORE WIND
CENTRE OF EXCELLENCE

Delivered by
CATAPULT
Offshore Renewable Energy

FLOATING OFFSHORE WIND TECHNOLOGY AND OPERATIONS REVIEW

ORE.CATAPULT.ORG.UK

AUTHOR // Luke Eatough
DATE // 28-01-2021

DISCLAIMER

Whilst the information contained in this report has been prepared and collated in good faith, ORE Catapult makes no representation or warranty (express or implied) as to the accuracy or completeness of the information contained herein nor shall we be liable for any loss or damage resultant from reliance on same.

CONTENTS

1 INTRODUCTION 7

2 TECHNOLOGY 8
- 2.1 Substructure 9
- 2.2 Mooring Systems 17
- 2.3 Electrical Infrastructure 27
- 2.4 Turbine 33

3 MARINE OPERATIONS 34
- 3.1 Assembly and Installation 34
- 3.2 Operations and Maintenance 37

4 GEOGRAPHICAL DISTRIBUTION 42
- 4.1 FOW Development Constraints 42
- 4.2 Offshore Wind Deployment in Scotland 42

5 LIFECYCLE 44
- 5.1 Lifecycle Phases 44

6 PORT REQUIREMENTS 46
- 6.1 Construction Phase 46
- 6.2 Operation Phase 48

7 COMMERCIAL DRIVERS 50
- 7.1 UK Offshore Wind Targets 50
- 7.2 Contracts for Difference 50
- 7.3 Cost of Electricity Drivers 51
- 7.4 Operational Factors 51
- 7.5 Economies of Scale 53
- 7.6 Supply Chain Capability 53

8 REFERENCES 54

LIST OF FIGURES

Figure 1	Subsystems of floating offshore wind turbine (adapted from (Ramboll, 2020))	8
Figure 2	Hywind spar substructure (Equinor, 2021)	11
Figure 3	TetraSpar spar substructure (Borg, et al., 2020)	12
Figure 4	WindFloat semi-submersible substructure (Principle Power, n.d.)	13
Figure 5	Ideol's Damping Pool barge substructure (Ideol, 2018)	14
Figure 6	GICON SOF TLP substructure (GICON SOF, n.d.)	15
Figure 7	FOW turbine degrees of freedom (Sant & Cuschieri, 2016)	16
Figure 8	Catenary (L) and taut (R) mooring configurations (Vryhof, n.d.)	18
Figure 9	Hywind Scotland catenary mooring configuration (featuring suction anchors) and array layout (Statoil, 2017)	19
Figure 10	Taut configurations: SBM's inclined leg TLP design (L) (SBM Offshore, 2016) and Pelastar's vertical leg TLP platform (R) (PELASTAR, n.d.)	20
Figure 11	Saitec's DemoSATH platform, featuring a single point mooring system (Saitec, 2020)	21
Figure 12	TetraSpar mooring configuration (linetype 1 is synthetic wire; linetypes 2-4 are chain of varying size) (Borg, et al., 2020)	22
Figure 13	Drag embedment anchors on the deck of an anchor handling vessel (Vryhof, 2020)	23
Figure 14	Driven pile anchor during deployment (Offshore Engineer, 2019)	24
Figure 15	Suction pile anchor during deployment (Intermoor, 2021)	24
Figure 16	Vertical load anchor (Vryhof, 2020)	25
Figure 17	GICON TLP gravity anchor solution (GICON, n.d.)	25
Figure 18	Hywind Scotland fairlead design (Statoil, 2016)	26
Figure 19	H-shackle (L) (Intermoor, 2021) and D-shackle (R) (EDP, n.d.)	26
Figure 20	Example of mooring line with buoyancy module and clump weight (Davidson & Ringwood, 2017)	27
Figure 21	Nordsee One inter array cable layout, which are of looped design (Nordsee One, n.d.)	28
Figure 22	Inter-array cable cross section (Ryota TANINOKI, 2017)	28
Figure 23	FOW dynamic array cable components (NREL, 2014)	29
Figure 24	Dynamic cable configuration options (Philipp R. Thies, 2011)	30
Figure 25	Hywind Scotland Pilot Park dynamic cable configuration (Statoil, 2016)	31
Figure 26	Fukushima floating offshore substation (Fukushima Offshore Wind Consortium, n.d.)	32
Figure 27	Evolution of wind turbine size and capacity (Bloomberg New Energy Finance, 2017)	33

Figure 28	Hywind spar assembly and load out (ALE, 2021) (Equinor, n.d.)	35
Figure 29	WindFloat semi-submersible assembly and load out (Wind Systems, 2019) (EDPR, 2019)	35
Figure 30	Turbine installation onto the Windfloat semi-submersible platform (L) and Hywind spar platform (R) (Recharge News, 2020) (Saipem, n.d.)	36
Figure 31	Sectoral Marine Plan for Offshore Wind Energy – Final Plan Options (Scottish Government, 2020)	43
Figure 32	Scottish marshalling and assembly ports (200km sailing distance outlined) (Arup, 2020)	47
Figure 33	Nigg Energy Park, which was used as the foundations staging port for the Moray East (fixed bottom) offshore wind farm (Nigg Energy Park, 2020)	47
Figure 34	Scottish O&M ports (L: CTV 75km sailing distance; R: SOV 150km sailing distance (Arup, 2020)	48
Figure 35	Port of Peterhead, which is used as the O&M base for Hywind Scotland Pilot Park (Peterhead Port Authority, 2021)	49
Figure 36	Indicative LCoE figures vs capacity factor for a range of generating technologies (C. Yuan, 2017)	52
Figure 37	Average offshore wind capacity factors for UK offshore wind farms during 2018-19 (ORE Catapult, 2019)	52
Figure 38	Production based availability (average and min-to-max) for UK offshore wind farms during 2018-19 (ORE Catapult, 2019)	53

LIST OF TABLES

Table 1	Summary of four substructure typologies	9
Table 2	Hywind substructure summary	11
Table 3	TetraSpar substructure summary	12
Table 4	WindFloat substructure summary (dimensions relate to Kincardine design)	13
Table 5	Damping Pool substructure summary (dimensions relate to EolMed design)	14
Table 6	GICON SOF substructure summary	15
Table 7	Overview of catenary and taut mooring systems	17
Table 8	Catenary mooring system examples	19
Table 9	Hub height and rotor dimensions for offshore wind turbines	33

NOMENCLATURE

AHV	Anchor Handling Vessel
DOF	Degrees of Freedom
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
FOW	Floating Offshore Wind
KOWL	Kincardine Offshore Windfarm Limited
NDT	Non-Destructive Testing
O&M	Operations and Maintenance
PBA	Production Based Availability
R&D	Research & Development
ROV	Remotely Operated Underwater Vehicle
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle

1 INTRODUCTION

This summary of floating offshore wind (FOW) has been prepared as a deliverable report for Work Package 1 of the FOW and Fishing Interaction Working Group and Roadmap project. This resource has been developed to be read in conjunction with An Overview of Scottish Fisheries Prepared for the Floating Offshore Wind Industry (delivered by Brown & May Marine Ltd.), and both documents address the same key themes across the two industries: Technology, Marine Operations, Geographical Distribution, Lifecycle, Port Requirements and Commercial Drivers.

The FOW and Fishing Interaction Working Group and Roadmap project was established by the Floating Offshore Wind Centre of Excellence to facilitate a stakeholder engagement process to identify potential interactions between the Scottish fishing sector and future commercial FOW farms. The challenges and potential opportunities associated with these interactions will also be assessed. The project's main output will be a roadmap outlining a portfolio of activities to address these challenges and exploit any opportunities as the industry develops. Throughout the course of the project, both this report and the Overview of Scottish Fisheries are intended to support and inform discussions as and when required.

The project is structured around three work packages (WPs):

1. Overview of FOW deployment and fishing interaction in Scotland;
2. Road map to support positive interaction between FOW and fishing in Scotland;
3. Facilitation.

WPs 1 & 2 are delivered by the Offshore Renewable Energy Catapult, and WP3 is delivered by Quaybridge Scotland Ltd.

Under WP1, high-level summaries of FOW and fishing technology and operations have been complied using available industry guidance and public domain resources. Both this document and the Overview of Scottish Fisheries report comprise the main deliverables of WP1. The two reports are intended to be used as reference documents during the project to help identify FOW and fishing interactions.

WP2 will include a series of workshops between the project's Working Group members. The aim of these workshops is to identify potential interactions between FOW and fishing, to assess the effect of these interactions, and to propose and prioritise relevant future research activities. It is intended that the deliverable reports of WP1 shall support and inform these workshops as required. The main deliverable of WP2 will be the roadmap outlining the portfolio of future research activities.

WP3 – facilitation of project delivery – involves the identification and engagement of key stakeholders, the provision of support during project workshops, and the input of knowledge and expertise as required across WPs 1 & 2.

The FOW and Fishing Interaction Working Group and Roadmap project represents a cross-industry effort to identify the actions that will help to balance the needs of Scottish fishermen and floating offshore wind farms. It is hoped that the project's final deliverable – the Floating Offshore Wind and Fishing Interaction Roadmap – will help to support constructive interaction between the two sectors in the future.

2 TECHNOLOGY

To date, deployment of floating offshore wind (FOW) technology in Scotland has been limited to pilot scale demonstrator projects. This is consistent with the position of other leading FOW markets globally. In order to meet the UK's current target of 1GW of FOW deployment by 2030, the development of commercial-scale arrays of floating turbine will be required.

It is generally accepted that 50 metres water depth represents the approximate current techno-economic limit to bottom-fixed offshore wind installation. FOW therefore offers a promising technical solution to accessing the stronger wind resources that are typically located further from shore, beyond this water depth limit.

As the bathymetry in many regions of Scotland's waters is well suited to FOW, it is highly likely that a significant proportion of the UK's future commercial FOW farms will be located within the Scottish exclusive economic zone (EEZ). Whilst these FOW farms will share many similarities with their bottom-fixed counterparts, there are also key distinctions between the two technologies that are of potentially high significance when considering interactions with other sectors, such as the fishing industry.

The following subsections will provide a high-level description of the key subsystems that a commercial-scale FOW farm would comprise, including the floating substructures, mooring systems and dynamic electrical cables. Currently, the same wind turbine designs are used for both floating and bottom-fixed wind, with limited divergence expected as the floating sector grows, therefore less focus will be placed on the turbine technology within this report.

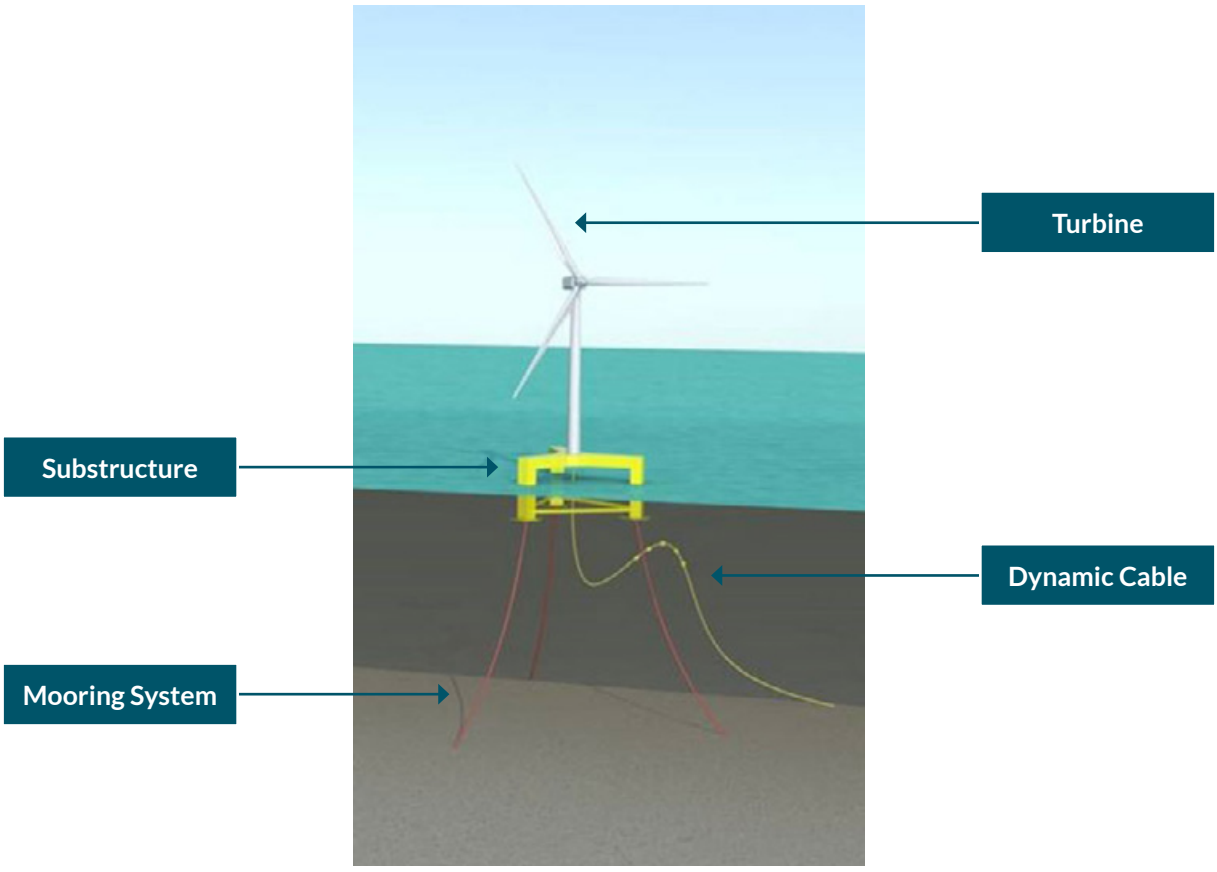


Figure 1: Subsystems of floating offshore wind turbine (adapted from (Ramboll, 2020))

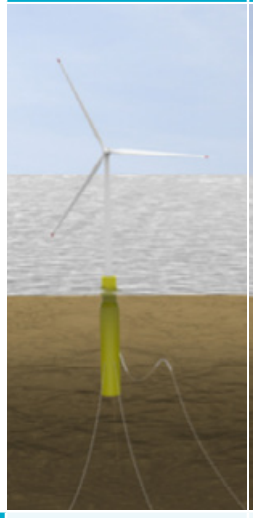
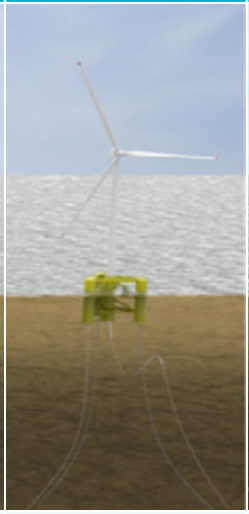
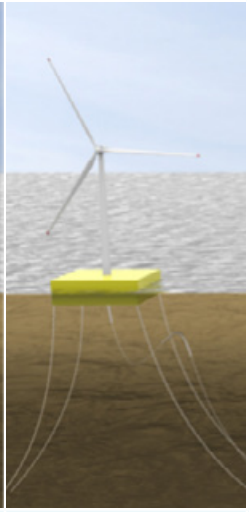
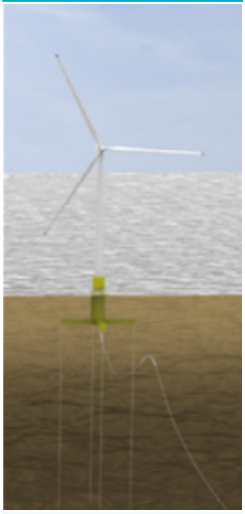
In many cases, the technical concepts utilised in FOW have a proven track record in the oil and gas industry. The technical and economic challenges of transferring these technologies from oil and gas to FOW often relate to the volume of deployment (e.g. dozens of smaller assets deployed in a commercial FOW farm, versus a small number of large assets utilised by the oil and gas sector), as well as novel requirements of FOW relating to system dynamics, operational efficiency, and cost reduction. These challenges are currently the focus of an international industrial and academic research and development (R&D) drive to address the commercial barriers to large scale FOW deployment, both in the UK and globally.

2.1 SUBSTRUCTURE

In contrast to bottom-fixed wind farms where the wind turbines are secured directly to the seabed (typically via monopile or jacket foundations), the turbines of FOW farms are installed on floating substructures that are anchored to the seabed via mooring systems. These substructures, or platforms, are typically fabricated from either steel or concrete, or a hybrid of the two materials. There are currently more than 50 different FOW substructure designs that are known to be under development (varying significantly in their technology readiness levels [TRL]), however they can generally be grouped into the following four substructure typologies:

- Spar;
- Semi-submersible;
- Barge;
- Tension leg platform (TLP).

The four substructure typologies are described in further detail in the following subsections. Table 1 provides a high-level, at-a-glance comparison. It should be noted that the dimensions are purely indicative and are based on available data relating to current, conventional designs.

	Spar	Semi-submersible	Barge	TLP
				
Primary stability mechanism	Ballast	Buoyancy	Buoyancy	Moorings
Mooring System	Catenary likely (taut / semi-taut possible)			Taut
Typical draft (m)	70-100	15-20	7-10	15-25
Typical length / width (m)	10-20 (conventional spar)	60-80	40-50	20-35

	Spar	Semi-submersible	Barge	TLP
Advantages	• Low sensitivity to wave motions. • Simpler design reduces cost and complexity of manufacturing.	• Smaller draft offers flexibility regarding wind farm water depth. • Shallow water quayside assembly and tow-to-port operations are supported by small draft and natural stability.	• Smaller draft offers flexibility regarding wind farm water depth. • Shallow water quayside assembly and tow-to-port operations are supported by small draft and natural stability. • Simpler design for manufacture and assembly (compared to semi-submersible).	• Excellent stability, once installed. • Small mooring footprint. • Smaller draft offers greater flexibility for wind farm depth and assembly facility.
Disadvantages	• Limited to deeper wind farm locations (+100 meters) due to large draft. Tow-to-port also challenging. • Assembly process requires deep water facility and expensive offshore heavy lift vessels.	• Heavier, more complex design can increase the cost of fabrication. • Greater sensitivity to wave loading.	• Greater sensitivity to wave loading. • Predominantly concrete designs require higher structural mass to achieve buoyancy.	• Reliance on mooring system for stability increases cost and complexity of assembly and towing processes. • Mooring system subject to higher stresses throughout project lifecycle. • Currently the least commercially advanced design.

Table 1: Summary of four substructure typologies

2.1.1 SPAR

Spar floating substructures are typically of a cylindrical design that in many ways resembles the monopile foundations commonly utilised in bottom-fixed offshore wind farms. Conventional spars have a large draft – the substructures can be up to 100 metres in height, with the majority of the structure submerged – and are therefore most likely to be deployed in water depths of >100 metres.

The spar is a ballast-stabilised design where seawater, or a combination of concrete and seawater, is used to lower the structure's centre of gravity to below its centre of buoyancy, thereby creating a natural righting motion when the platform is subject to pitch and roll motions. The primary role of a spar substructure's mooring system is therefore to provide station keeping, and catenary mooring configurations can be used (though designers may opt to deploy semi-taut or taut mooring configurations, either to provide greater heave control in certain environmental conditions, or to achieve cost reductions through reduced material usage in deeper waters).

The spar's favourable natural stability is supplemented by its relatively narrow cross-sectional area, small waterplane area and cylindrical form, meaning that it is less susceptible to wave loading than other FOW substructure designs. Additional advantages include the simplicity of its design, which includes relatively few active systems or welds and therefore improves the ease of fabrication.

The principal drawbacks of conventional spar designs generally relate to the large draft. This presents particular challenges related to assembly and installation, as shallow water port facilities are not suitable for assembly, and shallower sites (<100 meter depth) cannot be considered for FOW farm development using spar designs. Likewise, options will likely be limited – both in terms of port facilities and route to port – should a FOW turbine need to be disconnected and towed to port for maintenance.

Spar Case Study: Hywind

Design Name	Hywind
Owner	Equinor
Typology	Spar
Projects	Hywind Scotland
Material	Steel
Draft (m)	78
Substructure Length (m)	14.5
Substructure Width (m)	14.5
Substructure Height (m)	91
Mooring System	Catenary
Turbine Capacity	6MW

Table 2: Hywind substructure summary

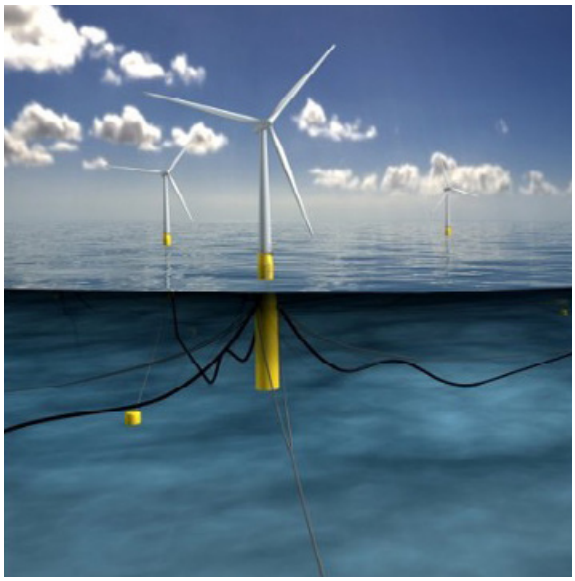


Figure 2: Hywind spar substructure (Equinor, 2021)

Spar Case Study: TetraSpar

In addition to the traditional spar structures utilised in the oil and gas sector, some FOW developers are exploring non-conventional, FOW-specific spar designs. One such example is Stiesdal Offshore Technology's TetraSpar design, which features a ballasted suspended keel. During the installation process, the keel is intended to be unballasted thereby elevating it to sea level and reducing the overall draft of the substructure. Upon arrival at the windfarm location, the keel can be ballasted and lowered to stabilise the substructure. This design is intended to facilitate a more cost-effective assembly and installation process by limiting the demands for quayside water depth and installation crane capacity (though it should be noted that towing the unballasted substructure may be more complex, as the structure will be less stable in this state). The TetraSpar is an earlier-stage concept than Hywind, with a 3.6MW prototype currently under construction and initial testing at sea planned for 2021.

Design Name	TetraSpar
Owner	Stiesdal Offshore Technologies
Typology	Spar (suspended weight)
Projects	Demonstrator under construction
Material	Steel
Draft (m)	66
Substructure Length (m)	67
Substructure Width (m)	67
Substructure Height (m)	80
Mooring System	Catenary
Turbine Capacity	3.6MW

Table 3: TetraSpar substructure summary

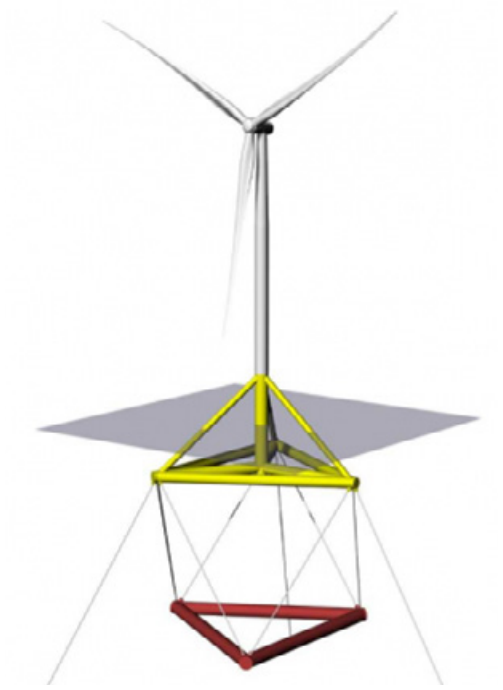


Figure 3: TetraSpar spar substructure (Borg, et al., 2020)

2.1.2 SEMI-SUBMERSIBLE

Semi-submersible floating substructures typically comprise three or four buoyant columns that are secured into a platform formation with connective bracing. Stability is primarily achieved through buoyancy tanks contained within the columns, though the columns may also contain either passive or active ballast systems (varying from design to design). Some designs also include a horizontal heave plate to create a drag force that resists heave motions due to wave and wind effects. Due to its inherent stability, as with spar platforms, the principal function of a semi-submersible's mooring system is to provide station keeping, and therefore catenary mooring configurations can be utilised (though in deeper waters, designers may opt to deploy semi-taut or taut mooring configurations to reduce material requirements).

Whilst there are a variety of semi-submersible designs for FOW applications, the platforms have a lower draft (typically 10-20 metres) which provides greater flexibility for the assembly and installation process. As there is no reliance on the use of deep-water sites, it is possible that standard commercial ports with typical quayside water depths can be used for the assembly and deployment of the platforms

(provided that the facilities meet other key requirements including sufficient available laydown area, ground bearing capacity and crane access). The semi-submersible's favourable draft increases a developer's options when selecting an assembly port and reduces the potential for complications due to sea depth when towing the completed platforms to site.

A principal drawback of semi-submersible substructures is that their heavier and more complex designs tend to result in higher manufacturing costs and material requirements. Furthermore, the substructure's greater exposed cross-sectional area at the water level means that semi-submersible designs are more susceptible to platform motions due to wave loading, and there is a higher risk of corrosion effects.

Semi-Submersible Case Study: WindFloat

Design Name	WindFloat
Owner	Principle Power
Typology	Semi-Submersible
Projects	WindFloat Atlantic (Portugal); Kincardine (Scotland)
Material	Steel
Draft (m)	20
Substructure Length (m)	75
Substructure Width (m)	75
Substructure Height (m)	30
Mooring System	Catenary
Turbine Capacity	9.5MW

Table 4: WindFloat substructure summary (specifications relate to Kincardine project)

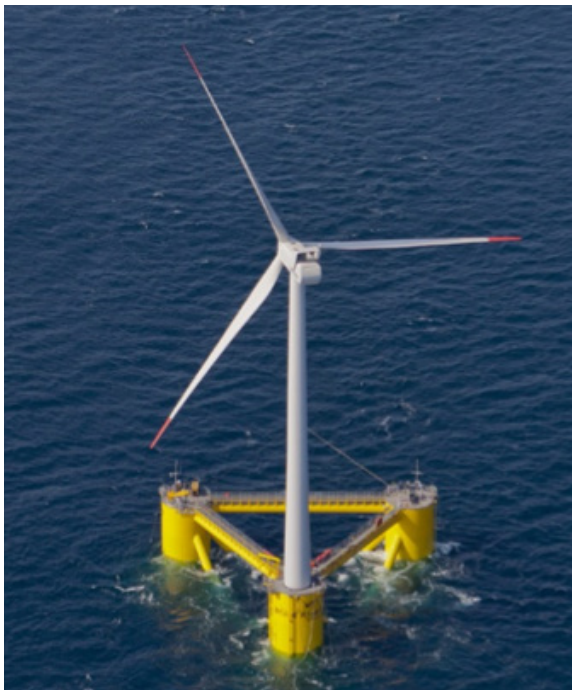


Figure 4: WindFloat semi-submersible substructure (Principle Power, n.d.)

2.1.3 BARGE

Of the four FOW substructure typologies, barge platforms are currently the least common design. Though they share a number of characteristics with semi-submersible substructures, barges are a simpler structure with a large waterplane area and buoyancy compartments distributed throughout the platform. Barges are primarily buoyancy stabilised and can therefore utilise catenary mooring systems. Ideol's Damping Pool platform – the most advanced barge design at the time of writing – includes a moonpool at the centre of the structure to help counteract wave induced loading and provide further stability.

As a rule, barges have the lowest draft of the four typologies (typically <10 metres) and thereby offer greater flexibility, both in terms of the choice of the assembly facility, as a deep-water quayside is not required, and the range of wind farm locations, as barges can technically be installed in shallow water sites (<40 metres).

In comparison to semi-submersible platforms, barges are simpler to manufacture and install. A principal drawback of the barge design is that its large waterplane area makes it more susceptible to wave loading, which may require careful consideration when selecting the platform's mooring system. Furthermore, barge designs, which are currently predominantly concrete, generally require a higher structural mass in order to achieve buoyancy.

Barge Case Study: Damping Pool

Design Name	Floatgen
Owner	Ideol
Typology	Barge
Projects	Floatgen; EolMed (both France)
Material	Concrete
Draft (m)	8
Substructure Length (m)	50
Substructure Width (m)	50
Substructure Height (m)	12
Mooring System	Catenary
Turbine Capacity	10MW

Table 5: Damping Pool substructure summary (specifications relate to EolMed project)

Figure 5: Ideol's Damping Pool barge substructure (Ideol, 2018)

2.1.4 TENSION LEG PLATFORM

The key distinguishing characteristic of the Tension Leg Platform (TLP) is that it derives its stability from its moorings, which generally comprise three to six anchored tendons that run either vertically or at a slight incline directly to the seabed. A typical TLP configuration includes a central column or frame upon which the turbine is installed, with a series of arms or surrounding lattice frame that connect to the mooring tendons.

A TLP's buoyancy tank, or tanks, exerts a buoyancy force that exceeds the weight of the platform, thereby establishing continuous tension between the platform and its anchors. In principle, once installed, this tension in the mooring system provides excellent stability for operational turbines, resisting pitch, roll, sway and yaw motions from wave and wind loading. The TLP's smaller water plane area further enhances stability by reducing the effects of wave loading (though the wave dynamics of shallow water sites are still expected to be challenging for TLP designs).

The taut mooring configuration means that the TLP has the smallest mooring footprint of the four substructure typologies. The platforms also usually have smaller dimensions – and therefore lower weight and material requirements – than the other substructure typologies. The TLP's shallow draft would provide developers with greater flexibility when considering assembly facilities, as a deep-water site would not be required.

Whilst there is a wealth of experience of TLP applications in the oil and gas sector, it is currently the least commercially advanced FOW platform concept. Some key design challenges still require addressing, particularly related to the mooring system. The mooring tendons and anchors must be able to withstand the higher and continuous stresses that they would be subject to throughout a wind farm's lifecycle. Higher grade materials, either steel or synthetic, will therefore be required, and designers may opt to include additional redundancy in the moorings in order to counter the higher risk of failure. For this reason, developers would be less likely to select TLP platforms when developing wind farms in locations that are subject to seismic activity. Furthermore, as TLP substructures are not inherently self-stable, the tow to site and installation process is likely to be more complex and potentially costly.

TLP Case Study: GICON SOF

Design Name	GICON SOF
Owner	GICON
Typology	TLP
Projects	Tank tested at small scale. No open sea testing to-date.
Material	Concrete-steel hybrid
Draft (m)	14
Substructure Length (m)	32
Substructure Width (m)	32
Substructure Height (m)	26
Mooring System	Taut
Turbine Capacity	6-10MW

Table 6: GICON SOF substructure summary

Figure 6: GICON SOF TLP substructure (GICON SOF, n.d.)

2.1.5 MATERIAL: STEEL & CONCRETE

Steel is currently the most common structural material choice for substructures. However, there are advantages and disadvantages to both materials, and a number of designs utilise concrete, or a combination of the two materials.

- **Steel** – There is a wealth of industry experience in the use of steel in offshore structures, and in terms of a project's environmental lifecycle cost, it is the easier material to recycle. Steel substructures can also achieve buoyancy with a lower structural mass, thereby improving the ease and cost of handling. However, steel is subject to corrosion, is the more expensive material per raw unit tonne, and is subject to the risk of price volatility.
- **Concrete** – Despite being favoured by fewer substructure designs, concrete can present some advantages. It has a lower cost than steel per unit tonne of raw material and can provide a long service life. However concrete substructures are generally heavier than a steel equivalent and with long curing times, thereby placing greater pressure on construction ports. They can also be more vulnerable to the impacts of frost.

Developers may also consider social impacts when considering the choice of material. A local supply chain might have stronger capability in handling one material or the other. While it may be easier to increase local content for a project that utilises concrete, some might take the view that creating work for the steel industry can generate more skilled local jobs (though the UK is generally outcompeted on price with regards to primary steel fabrication).

2.1.6 PLATFORM MOTIONS

The six degrees of freedom (DOF) of a FOW turbine are outlined in Figure 7. Due to their taut moorings, TLPs would in principle have the smallest displacements, particularly in the pitch, roll, sway and yaw directions. Substructures with catenary moorings have greater freedom to move within these 6 DOFs, and those with a greater waterplane area and platform cross-section may also be liable to undergo greater motions. Regardless of the platform design, the scale of platform displacements will be highly weather dependent.

There is limited operational data in the public domain relating to FOW platform motions. However, initial data released from the Hywind project indicates that the spar design's maximum static (wind-driven) displacement is approximately 10 metres, while maximum dynamic (wind plus wave) displacement can approach 15 metres.

Natural oscillation periods for surge and sway motions may be in the region of 120 seconds for spar, semi-submersible and barge designs, but closer to 40 seconds for TLP substructures. Similarly, oscillation periods for pitch, roll and heave motions may be 20-30 seconds for spar, semi-submersible and barge designs, and closer to 5 seconds for TLP platforms. Based on these indicative figures, the theoretical favourable stability of the TLP is outlined by its restricted platform motions, relative to other substructure typologies.

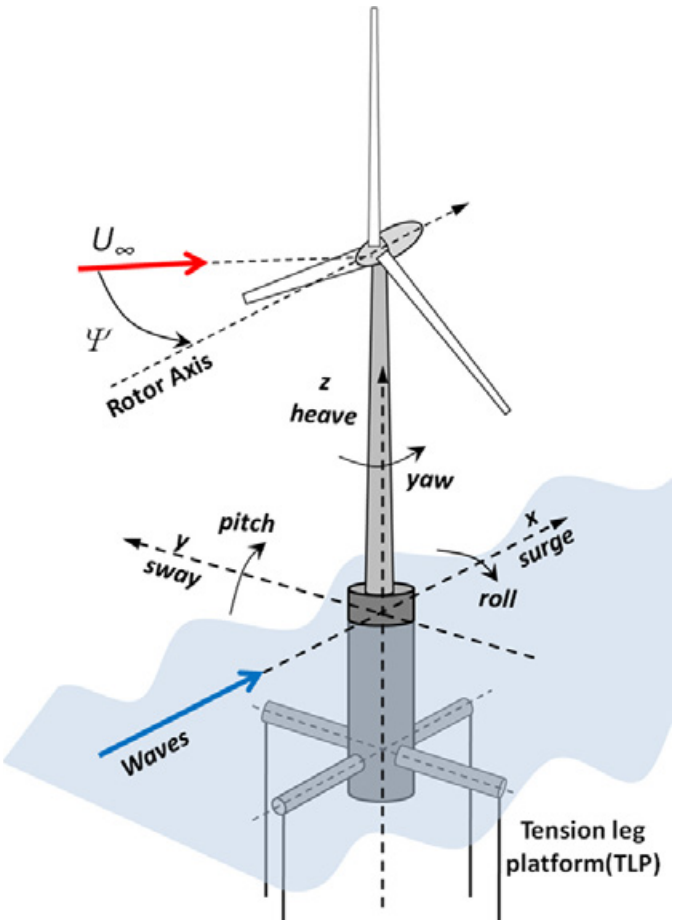


Figure 7: FOW turbine degrees of freedom (Sant & Cuschieri, 2016)

2.2 MOORING SYSTEMS

A FOW turbine's mooring system provides the mechanical connection between the floating substructure and the seabed. The oil and gas industry has a proven track record in the application of mooring systems for floating offshore energy infrastructure, and the initial mooring solutions deployed in FOW have been based on those designs. Nevertheless, FOW mooring systems are the subject of ongoing research and development work and further innovation is required for FOW to become commercially competitive alongside bottom-fixed wind.

Much of the research focus is on achieving further cost reductions through an improved understanding of typical FOW mooring system fatigue mechanisms, the development of lower cost novel materials for mooring lines and auxiliary components, and exploring more efficient installation methods. A key issue identified by the industry is that the standards used in the oil and gas sector for mooring system design and inspection do not fully meet the requirements of FOW farm developers. Full commercialisation of FOW technology will therefore depend partly on the development of bespoke standards that account for the fatigue load cycles of FOW mooring systems due to turbine-platform dynamics. Furthermore, given that the data from oil and gas operations indicates that a mooring line failure is likely to occur during the lifecycle of a commercial scale FOW farm, designing for the appropriate level of system redundancy will enable developers to achieve the required balance between cost and risk.

2.2.1 CONFIGURATIONS

The mooring system configuration deployed at a given FOW farm will depend on a number of factors, including the substructure design, water depth, and seabed and environmental conditions.

Whilst there are a range of configuration options currently under consideration by FOW technology developers, broadly speaking they can be grouped into two categories: catenary and taut systems. The number of mooring lines deployed per FOW turbine will vary depending on the project's design requirements and approach to redundancy, though typically they will range between three and six per turbine (though as many as nine mooring lines per turbine have been considered in some instances). The type of mooring configuration utilised will partly determine the type of anchor that a developer can select (further detail is provided in Section 2.2.3).

	Catenary	Taut
Restoring Force	• Weight of mooring line	• Mooring line tension
Seabed connection	• Horizontal	• Varies between vertical and 45 degrees, depending on design
Material	• Chain, or chain-rope combination	• Steel or synthetic tendon
Advantages	• Offers anchor system cost savings: simpler installation process, and the anchor is not required to tolerate uplift.	• Smaller mooring footprint. • Less seabed disruption during operational phase.
Disadvantages	• Larger mooring footprint. • Greater environmental disruption at seabed touchdown point during operational phase (due to horizontal movement of chain).	• Costly anchor systems required to withstand vertical loading. • Installation process more costly and complex.

Table 7: Overview of catenary and taut mooring systems

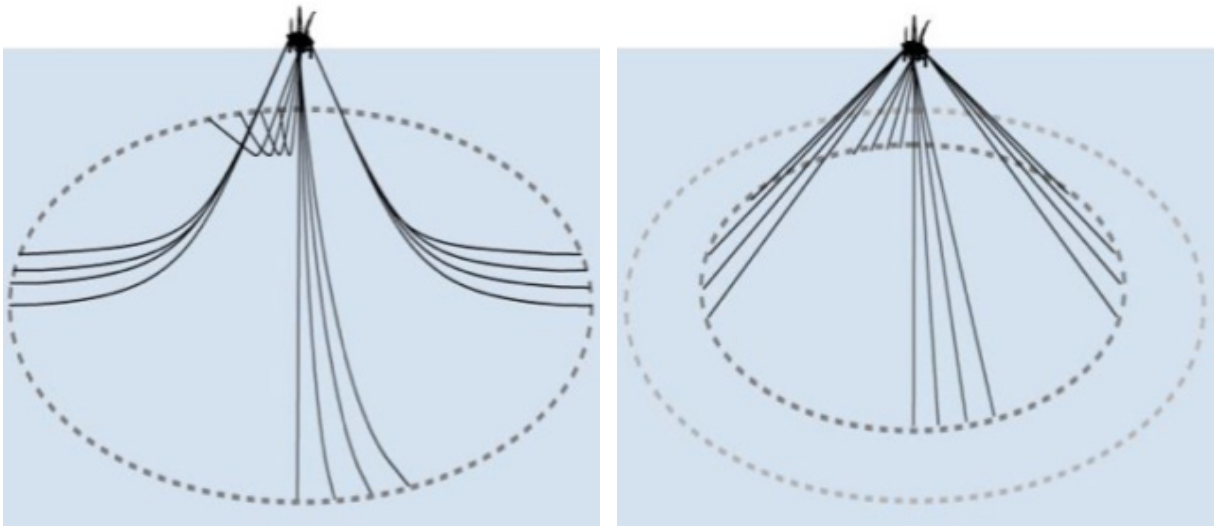


Figure 8: Catenary (L) and taut (R) mooring configurations (Vryhof, n.d.)

Catenary Systems

Catenary systems are the most widely deployed FOW mooring configuration to date, with both Hywind Scotland Pilot Park and Kincardine Offshore Wind Farm (currently under development) opting for these arrangements. The mooring systems utilised in the earliest FOW projects have been predominantly chain-based solutions, with some developers including sections of synthetic rope within the mooring lines. The length of a mooring line in a catenary configuration is greater than the water depth, which leads to a larger footprint compared to taut systems. As the system is installed with a degree of slack, the mooring lines are allowed to hang freely in the water column between the two fixed points at the turbine substructure and the seabed anchors, thereby defining a catenary curve as determined by the chain's response to the force of gravity. In a typical catenary arrangement, the lowest section of a mooring line will lie horizontally on the seabed as it approaches the anchor.

In the case of ballast- and buoyancy-stabilised FOW substructures (spar, semi-submersible and barge designs), the primary role of the mooring system is to provide station keeping, and therefore catenary configurations may be utilised provided the environmental conditions at a wind farm location do not rule out their economic viability. The optimal depth for catenary systems is deemed to be in the 100-250-metre range. The dynamics of shallower sites necessitate larger mooring systems that can withstand the additional fatigue loading, and such systems are currently considered to be prohibitively expensive without further technical developments. In deeper waters beyond the 250-metre range, the additional material requirements of catenary systems can limit a FOW farm's commercial viability.

The anchors of catenary mooring systems are only required to withstand horizontal loading, therefore traditional drag embedment anchors can be utilised provided the site has suitable seabed characteristics. This offers the advantage of a simpler installation process that avoids the noise and environmental impact of other solutions, such as driven pile anchors. However, designers will need to consider that the section of a catenary mooring line that lies on the seabed will be subject to additional scour and abrasion, compared to taut configurations.

The length of a catenary mooring line will depend partly on the water depth, though the mooring design must also account for the site's dynamics. Examples of FOW catenary mooring dimensions are included in Table 8.

	Substructure type	Water depth	Mooring lines per turbine	Mooring radius
Kincardine Offshore Wind Farm	Semi-Submersible	60-80 metres	4	540-720 metres (seabed touchdown approx. 250 metres from turbine)
Hywind Scotland Pilot Park	Spar	100-117 metres	3	690-875 metres

Table 8: Catenary mooring system examples

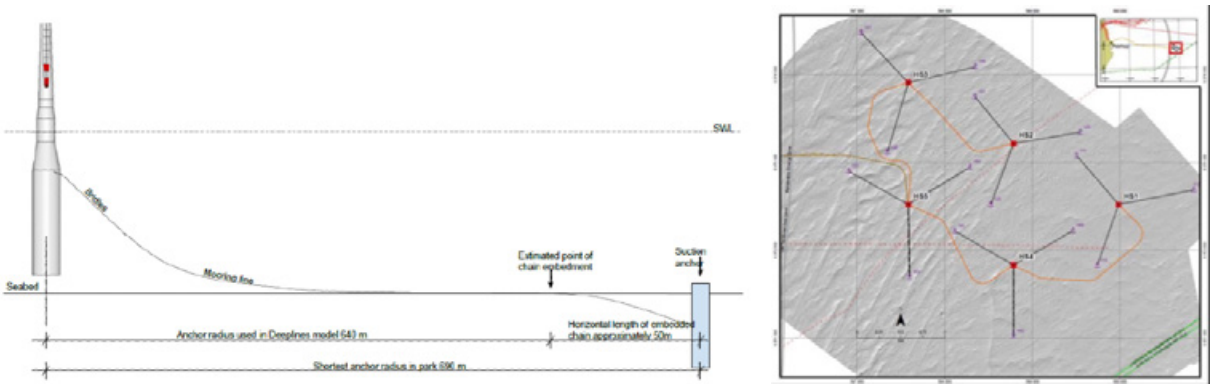


Figure 9: Hywind Scotland catenary mooring configuration (featuring suction anchors) and array layout (Statoil, 2017)

Taut Systems

In contrast to catenary systems, the mooring lines in taut configurations are installed under tension so that they run directly from the floating substructure to the anchors, either vertically or at a slight incline. This applies an elastic restoring force that opposes platform motions due to wave and wind effects and offers greater turbine stability than catenary solutions.

Taut systems are necessarily required by TLP substructures which are mooring-stabilised designs and therefore rely on the tension in the mooring system to supply a righting force against roll, pitch and sway motions. Nevertheless, depending on the circumstances some developers may opt to use taut mooring systems with other substructure typologies. For instance, if the water depth at a wind farm location exceeds the economic limit for catenary solutions, taut systems may offer a cost advantage due to the material savings that result from the shorter mooring lines.

The smaller mooring footprint of the taut configuration means that each FOW turbine occupies less seabed than if an equivalent catenary solution had been selected, which, once installed, offers potential advantages from an environmental and consenting perspective. Challenges related to taut configurations include the dependence on anchor systems that can withstand high vertical loads, or a combination of vertical and horizontal loading. Such systems can be more costly and complex to install than simple drag embedment solutions and may also cause greater environmental disturbance during the installation process. Designers must also be careful to select mooring lines with the appropriate level of elasticity for the local environmental conditions to ensure that the system will not be overloaded by the site's wave characteristics. For this reason, taut moorings may not be suitable for locations that are more prone to seismic activity. Furthermore, the challenges of shallower sites that affect catenary solutions also apply to taut mooring configurations.

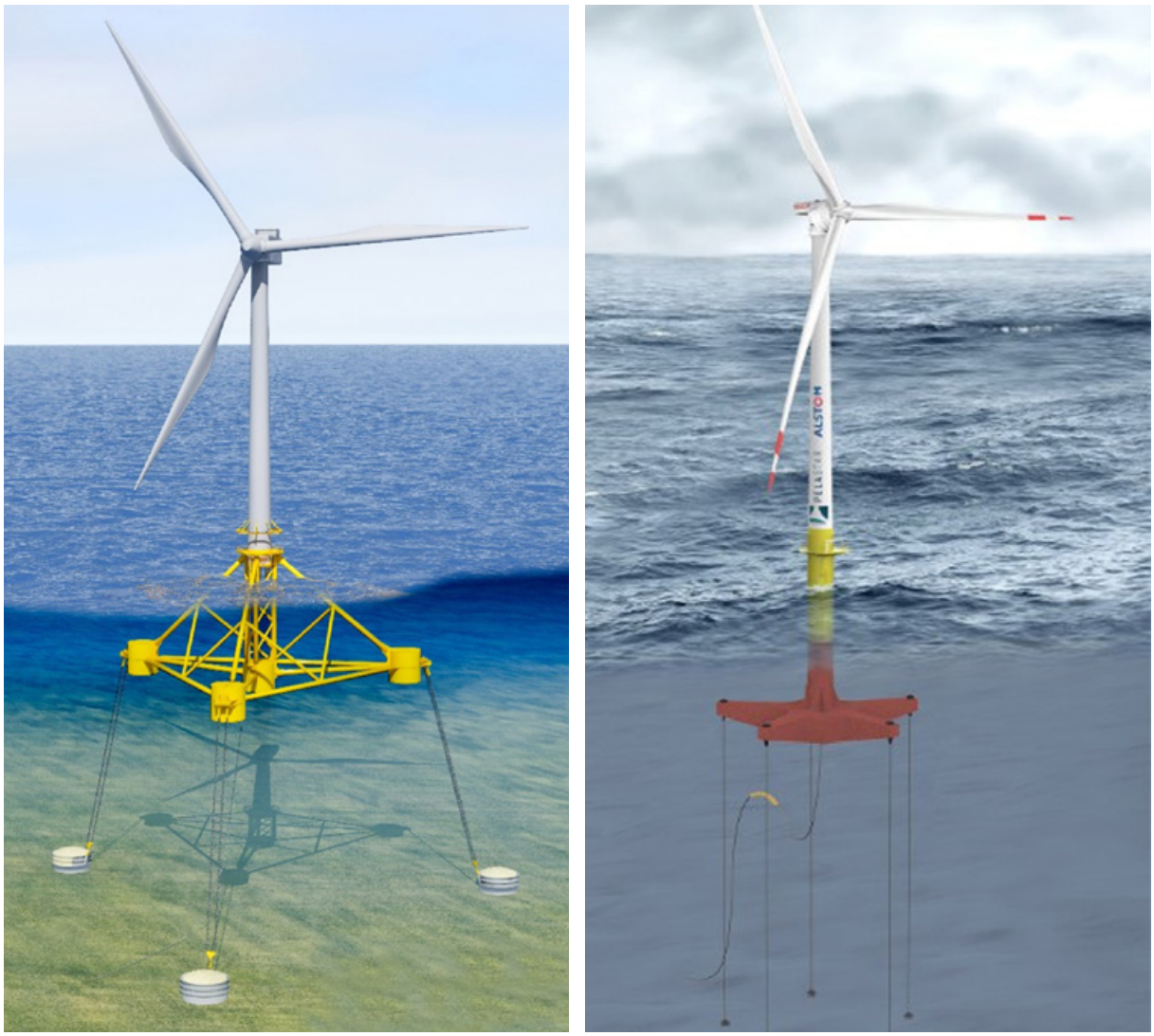


Figure 10: Taut configurations: SBM's inclined leg TLP design (L) (SBM Offshore, 2016) and Pelastar's vertical leg TLP platform (R) (PELASTAR, n.d.)

While the above description outlines catenary and taut mooring systems as distinct options, designers may opt for a hybrid, semi-taut approach. A semi-taut system incorporates both taut and catenary elements and could offer cost advantages in deeper water where the material requirements of catenary systems are prohibitively high.

Spread vs Single Point Moorings

The vast majority of FOW turbines deployed to date have featured spread mooring systems, whereby each mooring line is connected to a separate point on the floating substructure. There is some interest in whether the use of single point mooring solutions might offer future cost advantages and enable quicker substructure installation, as well as disconnection and reconnection for maintenance, for platforms that utilise catenary configurations. Single point systems include a buoy or "turret" that connect all of a FOW turbine's mooring lines to a single component, around which the FOW substructure is able to yaw passively into the wind. Despite a proven track record in oil and gas, FOW single point mooring systems remain an early-stage technology, with spread mooring systems very much the more commercially advanced option.

Figure 11: Saitec's DemoSATH platform, featuring a single point mooring system (Saitec, 2020)

2.2.2 MOORING LINE MATERIALS

Chain

To date, steel chain – both studded and studless – has been the most commonly used material for FOW mooring lines. FOW mooring chain designs have been based on oil and gas mooring technologies, hence chain is a more commercially mature option. When used in catenary configurations, steel chain offers the advantage that, due to its weight, the lower section of the mooring line is more likely to remain on the seabed and therefore avoid applying vertical loads to drag embedment anchors that are unable to tolerate uplift. Moreover, chain is more likely to withstand the abrasion effects resulting from seabed interaction. Chain applications for FOW mooring are limited to catenary and semi-taut configurations. Also, compared to alternative materials, the added weight and dimensions of chain mooring lines requires greater handling capacity during the installation process.

Wire Rope

Like chains, wire rope mooring lines are also fabricated from steel, though they provide advantages over chain in terms of both weight and elasticity properties, whilst offering the same breaking point. However, wire ropes are more susceptible to corrosion and damage, and may need to be coated with a synthetic lining in order to improve their durability. Wire ropes can be deployed in both catenary and taut configurations.

Synthetic Rope

By comparison, synthetic rope offers a more novel mooring line material option. With a track record of application in the oil and gas sector, it is regarded by developers as a promising technology that could enable future FOW cost reductions, but with further qualification and development required in order for it to reach full maturity for FOW applications. Synthetic material options include nylon, polyester and high-modulus polyethylene (HMPE), with each displaying varying material properties. Advantages are expected in terms of weight and fatigue performance, as well as reduced material and installation vessel requirements.

Synthetic rope is considered to be well suited to taut configurations and less cost sensitive to depth than steel, hence it could be a preferred mooring material for TLP substructures and deeper water FOW farms. Additionally, it may offer potential benefits for very shallow sites where the hydrodynamic conditions require a mooring system with less stiff material properties (indeed, nylon was used for sections of the mooring system for Ideol's Floatgen demonstrator, which was installed in water depths of 33 metres).

In the case of catenary systems, the industry appears to be tending towards the selection of mooring systems that comprise multiple materials. Chain is likely to be used at the seabed connection, and potentially at the substructure connection, with wire or synthetic rope used within the rest of the water column. For example, the Hywind Scotland FOW farm deployed a combination of chain and wire rope for its moorings, while Ideol's Floatgen demonstrator and Stiesdal Offshore Technology's planned TetraSpar demonstrator both include a combination of chain and synthetic rope.

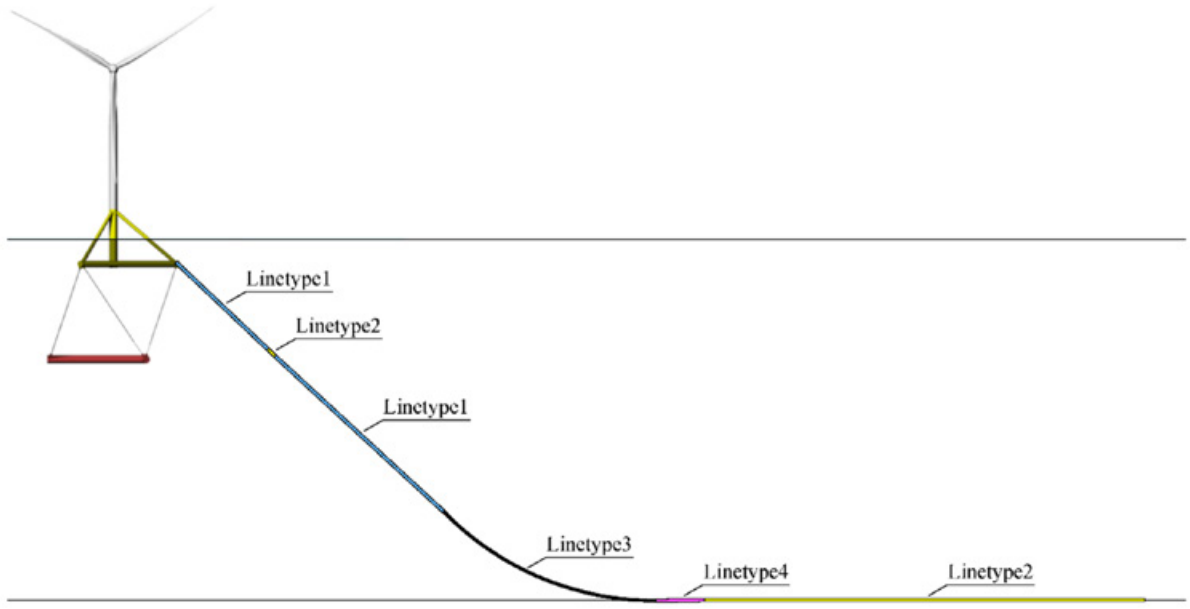


Figure 12: TetraSpar mooring configuration (linetype 1 is synthetic wire; linetypes 2-4 are chain of varying size)

2.2.3 COMPONENTS

FOW mooring systems comprise the primary components of mooring lines and anchors, along with an assembly of auxiliary components, including fairleads, shackles, buoyancy modules and clump weights. The exact combination of components used in a given project will depend on the chosen substructure design, the selected mooring configuration, the site's environmental conditions, as well as economic considerations.

Mooring Lines

Mooring lines connect a floating substructure to its seabed anchors. They occupy the majority of the water column, thereby constituting the main element of the FOW mooring system. According to a project's requirements, the mooring lines can be assembled in a range of configurations (see 2.2.1) and can be fabricated using from a number of materials (see 2.2.2).

Anchors

As with mooring lines, the type of anchor selected for a FOW project will vary depending on the substructure technology selected, the mooring configuration, as well as the seabed conditions. A range of anchor types have either been deployed or are being considered for deployment at early FOW pilot farms and demonstrators. The key anchor types that might be considered for a FOW farm are outlined in further detail below, and a principal factor that will guide a developer's selection is whether there is a requirement to tolerate vertical loading.

- **Drag Embedment Anchors** – A common anchor design that comprises a shank and fluke configuration that is designed, when deployed from a vessel and dragged along the seabed, to penetrate the soil. The positioning of the fluke is such that, once embedded, the anchor has a high horizontal holding capacity. This anchor type is therefore well-suited to catenary mooring configurations, and, provided the seabed type is not too hard to impede, FOW developers may favour its simple installation process and ease of decommissioning. Traditional drag embedment anchors are not designed to withstand vertical loading and are therefore not compatible with taut mooring configurations.

Figure 13: Drag embedment anchors on the deck of an anchor handling vessel (Vryhof, 2020)

- **Driven Pile Anchors** – Generally of a cylindrical tube design, driven pile anchors are installed deep into the seabed via a hydraulic pile driver. High friction forces and lateral soil resistance enable the pile to withstand vertical and horizontal loading, respectively. Driven pile anchors are suited to a broader range of seabed types, however the noise generated during installation and a more challenging decommissioning process could constitute more significant environmental impacts.

Figure 14: Driven pile anchor during deployment (Offshore Engineer, 2019)

- **Suction Pile Anchor** – A variation on the driven pile anchor, the suction anchor has a wider cylindrical form and is closed at the top. During the installation process, water is pumped out of the pile in order to create a vacuum. This pressure difference causes the anchor to become embedded into the seabed. The suction pile offers advantages over the driven pile in that it allows for easier installation and decommissioning, with reduced environmental impacts.

Figure 15: Suction pile anchor during deployment (Intermoor, 2021)

- **Vertical Load Anchors** – Similar in design and installation method to drag embedment anchors, though installed to a greater depth, vertical load anchors allow for rotation about the shank-fluke connection in order to enable omnidirectional loading. As a result, vertical load anchors can be utilised in both catenary and taut mooring configurations.

1. Angle adjuster sets anchor into vertical mode once installation load has been reached
2. Chain or wire configuration ensures extreme low installation resistance and deep penetration
3. Large fluke surface to create holding power
4. Robust fluke/chain configuration withstands repetitious handling in mobile applications
5. Wire shank arrangement in combination with fluke allows omnidirectional loading of the anchor

Figure 16: Vertical load anchor (Vryhof, 2020)

- **Gravity Anchors** – A simple anchor concept, gravity anchors rely on weight and seabed friction to provide a holding force. Developers may be more likely to select gravity anchors for taut configurations where the emphasis is on resistance to vertical loading, though they could also be utilised for catenary systems. Gravity anchors require hard seabed conditions, and their weight may present handling challenges and increase the cost of installation and decommissioning.

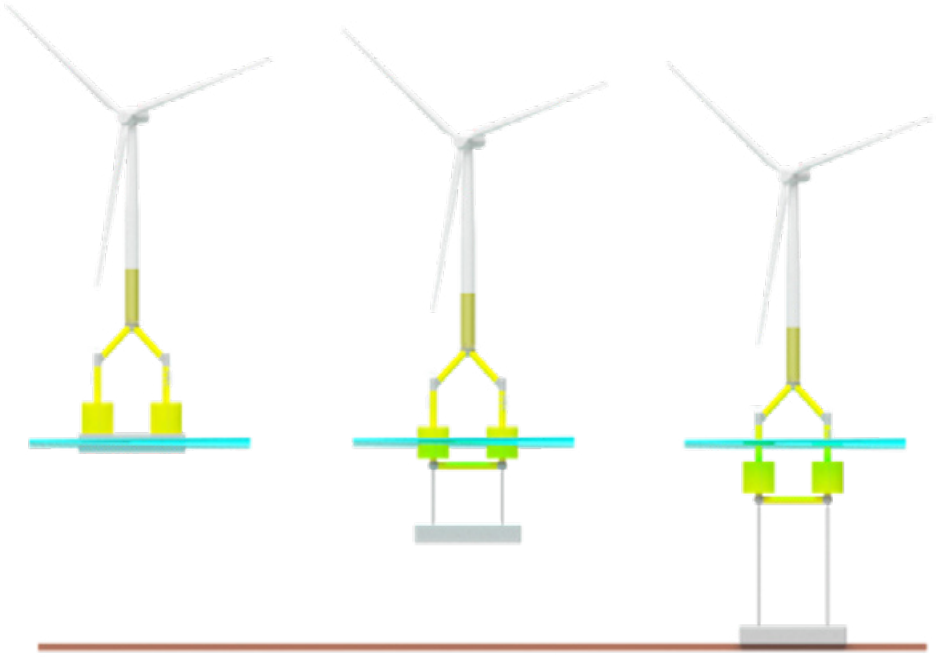


Figure 17: GICON TLP gravity anchor solution (GICON, n.d.)

Fairleads & Chain Stoppers

The connection point between the mooring system and the floating substructure is provided by a fairlead and chain stopper configuration. The exact assembly will depend on the requirements of the substructure and mooring system design. Designers will need to consider that, due to floater motions, out of plane bending moments will be applied to the mooring line at this connection point. Some substructures will incorporate winches in order to apply tension to the mooring lines, while in other designs, anchor handling vessels may be deployed to perform this role.

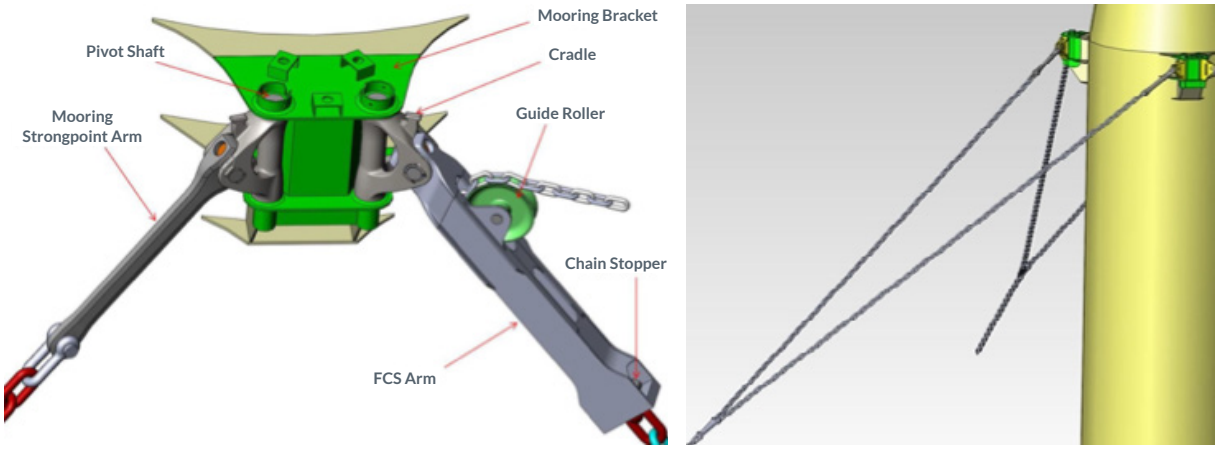


Figure 18: Hywind Scotland fairlead design (Statoil, 2016)

Connectors

In-line connectors are used to connect two sections of a mooring line, for example in mooring systems where multiple material types have been selected. H-link connectors can be used as joining shackles between two mooring line sections (e.g. chain-synthetic or synthetic-synthetic connections), whilst D type shackles can also be used, either as anchor shackles or as joining shackles.

Figure 19: H-shackle (L) (Intermoor, 2021) and D-shackle (R) (EDP, n.d.)

Buoyancy Modules and Clump Weights

Depending on the environmental conditions of the wind farm location, mooring designers may opt to add buoyancy modules or clump weights to the mooring lines. Buoyancy modules can be deployed to decouple the mooring lines from platform motions, and in deeper water sites they may be used to reduce the weight of the mooring lines supported by the substructure. On the other hand, clump weights can be added to the mooring system if an additional downward tension component is required for stability, which may be of benefit in dynamic shallow water sites.

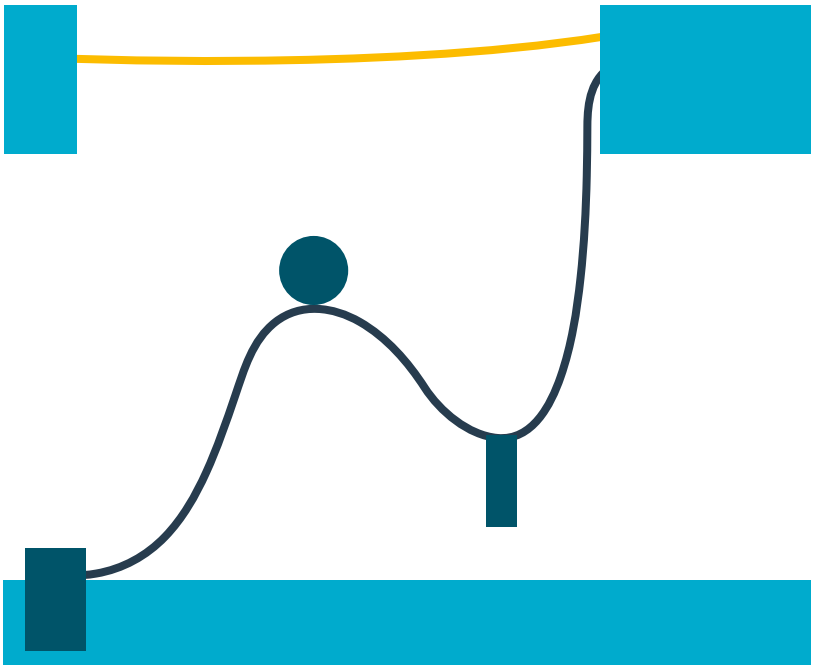


Figure 20: Example of mooring line with buoyancy module and clump weight (Davidson & Ringwood, 2017)

2.3 ELECTRICAL INFRASTRUCTURE

A commercial FOW farm will have the same electrical requirements as an equivalent bottom-fixed wind farm. However, the added dynamics of a FOW farm mean that further developments are required in respect of the mechanical performance of a project's key electrical infrastructure subsystems. The inter-array cables that connect the turbines within a FOW farm to the offshore substation will need to be of a dynamic design that can withstand the additional fatigue loading caused by the platform motions. Furthermore, floating substation designs are considered as a possibility for future deeper water FOW farms, which, if realised commercially, will require the development of high voltage dynamic cables for power export to shore.

2.3.1 DYNAMIC INTER ARRAY CABLES

A major component of a wind farm's electrical infrastructure is the inter-array cabling that provides the electrical connection between each of the turbines and the offshore substation. Groups of turbines can be connected to the substation either in strings or loops (termed "radially" or "ringed"), as determined during the array optimisation design phase.

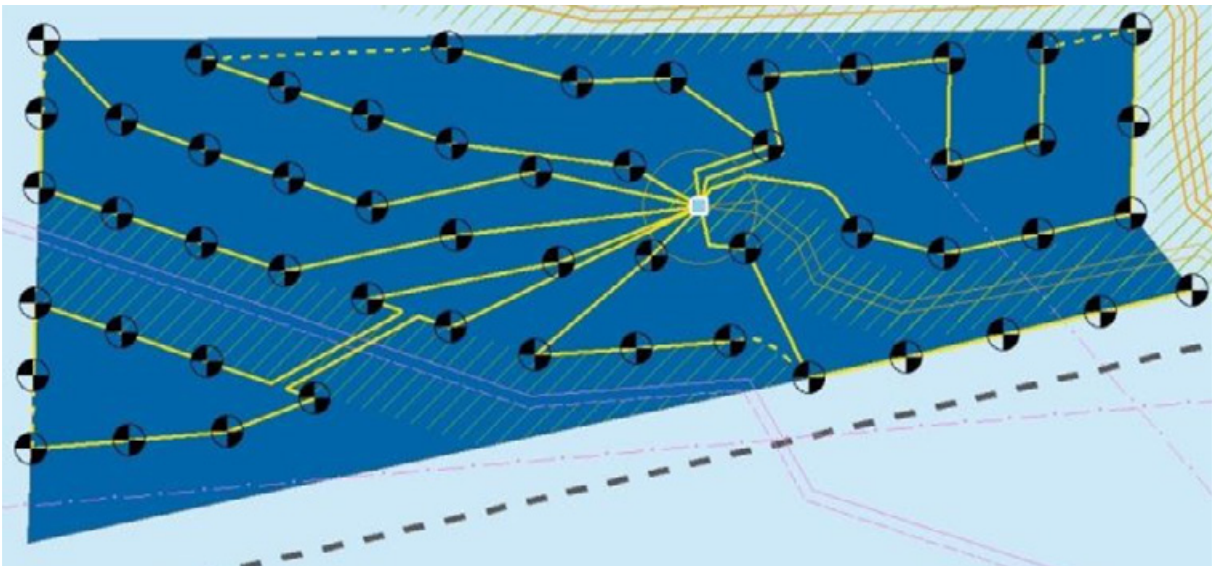


Figure 21: Nordsee One inter array cable layout, which are of looped design (Nordsee One, n.d.)

Inter-array cables with 33kV rating have commonly been deployed at offshore wind farms, though as turbine capacities continue to increase, 66kV inter-array cables are increasingly being considered by developers. A typical cable design includes three electrical cores (either copper or aluminium), a fibre optic cable for data transfer, electrical insulation and shielding, and an armoured sheath for external mechanical and impact protection. Inter-array cables are more likely to be of wet design, meaning that water is allowed to migrate to the insulation layer and conductors.

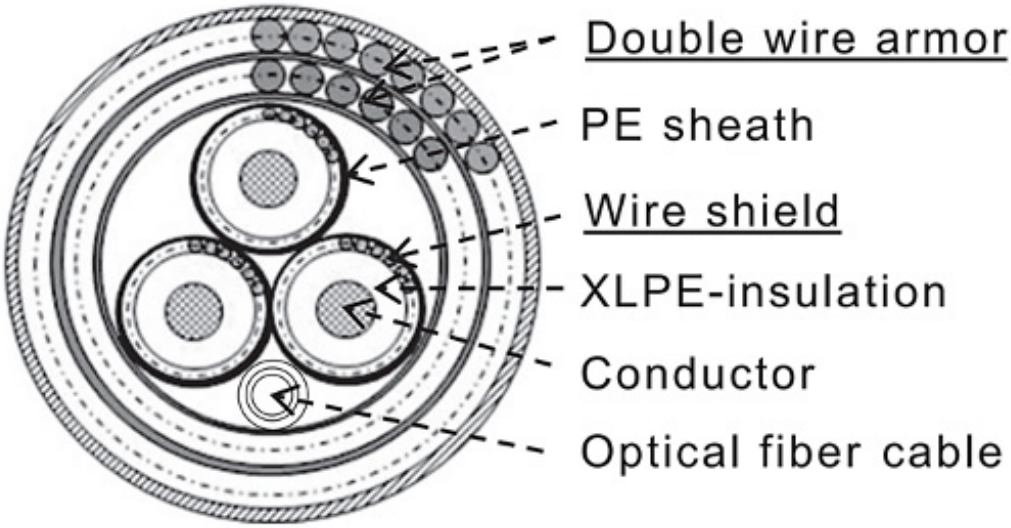


Figure 22: Inter-array cable cross section (Ryota TANINOKI, 2017)

Due to the inherent motions of floating substructures, FOW farms require dynamic inter-array cables that are mechanically designed to withstand the additional bending moments that they will be subject to through a project's lifecycle. The external armour is a critical component for fatigue, particularly at connection points such as the substructure hang off and the seabed touchdown. Contra-helical steel wire armour is likely to be utilised, rather than the traditional lead armour used for subsea cables, as this offers greater tensile strength and bend stiffness. Dynamic cabling is only required between the substructure and the seabed, and static cabling can be used for the sections of the inter-array cables that run along the seabed.

A FOW farm's inter array dynamic cable system will incorporate a range of auxiliary components, including:

- **Bend Stiffener** – A dynamic bend stiffener and latching mechanism is used to connect the dynamic cable to the floating substructure and to limit the bending moments applied to the cable at the floater hang off point. The substructure connection point will likely be protected by a J-tube.
- **Connector** – The main electrical termination between the cable and substructure. Dry-mate connectors are a mature technology, though their connection and reconnection must take place out of the water. Wet-mate connectors, which can be disconnected and reconnected underwater, are an area of technology development, though they may present additional cost to the system.
- **Buoyancy Module**s – As with mooring lines, buoyancy modules can also be applied to FOW dynamic cables to decouple the inter-array cable system from the floating platform motions and improve their fatigue life. The upward force applied can also help to reduce weight of the cable system, which may be of particular advantage in deeper water sites where greater cable lengths are required.
- **Touchdown Protection** – A protective sleeve may be applied at the seabed touchdown point to provide abrasion protection.
- **Transition Joints** – Used to connect the dynamic and static cable sections at their connection point on the seabed.

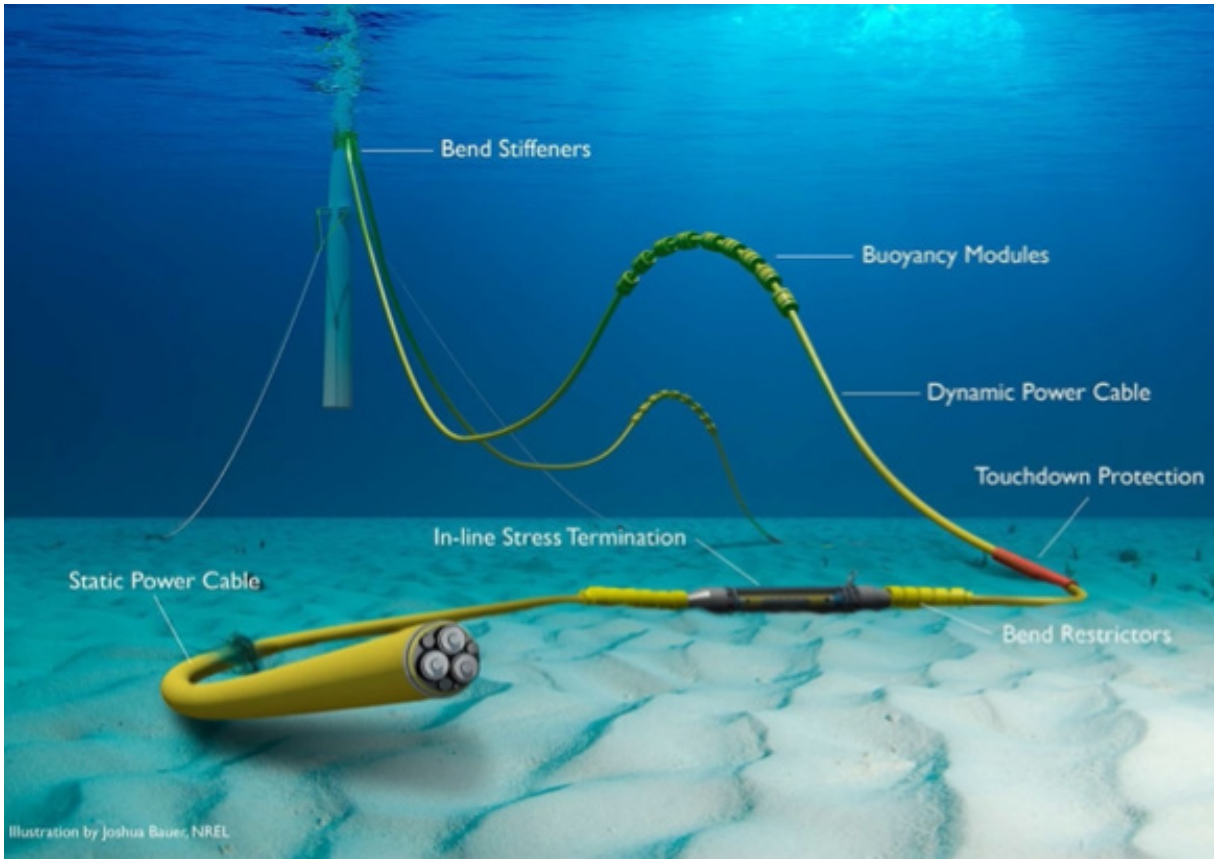


Figure 23: FOW dynamic array cable components (NREL, 2014)

Designers will opt for a dynamic cable configuration that most is likely to minimise fatigue, taking into account the motions of the chosen substructure type, the chosen cable's properties, water depth, wave loading, and the potential for marine growth.

- **Free Hanging / Catenary** – The simplest and cheapest configuration. In more dynamic sites, this arrangement could leave the cable system exposed to undue motions.
- **Lazy Wave** – The inclusion of buoyancy modules to create a lazy wave configuration adds cost to the system, but decouples the cable from floating platform motions. If marine growth is likely to accumulate on the inter-array cables, this configuration can help the system to cope with the added weight.
- **Steep Wave** – A similar configuration to the lazy wave, but with a bend stiffener and fixed base included at the seabed touchdown point. This adds further cost still to the system, as well as installation complexities, but provides added control that may be of benefit if the wind farm is likely to experience strong lateral ocean currents.
- **Lazy S** – Comparable to the lazy wave configuration, but with a moored subsea buoy used instead of buoyancy modules. Adds further cost and complexity to the system and may not be economically viable for use on most individual cables. The lazy S configuration offers designers greater control over the location of a cable's mid water bend. This may be of particular use for the inter-array cables that converge towards a substation, where cable separation distances need to be carefully managed.
- **Steep S** – Features the moored subsea buoy of the lazy S configuration and the fixed seabed touchdown connection of the steep wave arrangement.
- **Chinese Lantern** – Enables a direct vertical connection between the floating substructure and seabed. The inclusion of buoyancy modules creates a controlled section of cable slack that allows for greater heave platform motions.

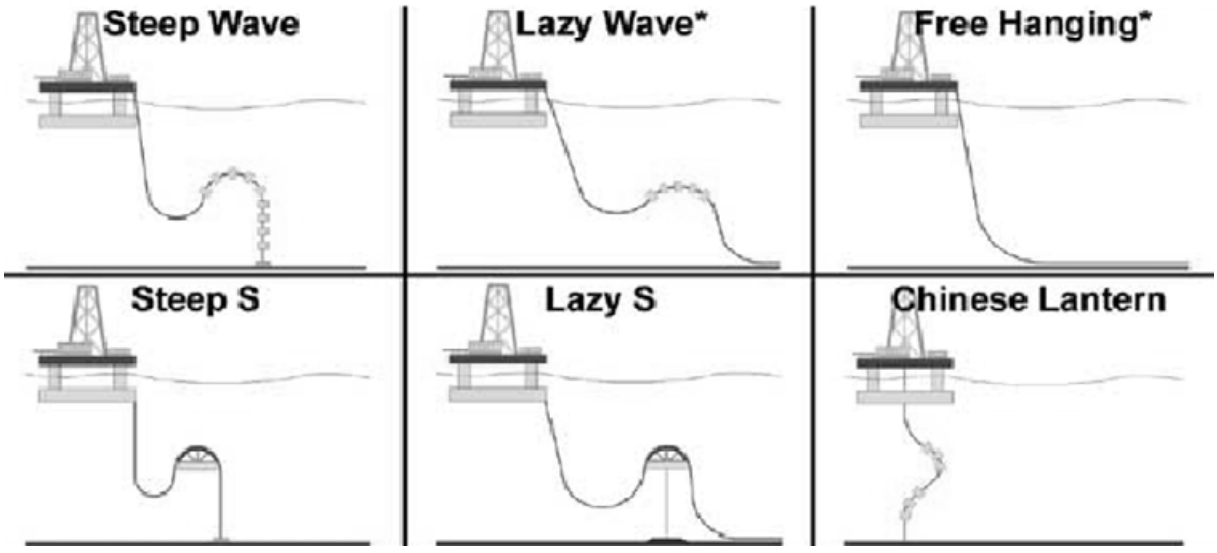


Figure 24: Dynamic cable configuration options (Philipp R. Thies, 2011)

The choice of cable configuration will impact the length of the dynamic section of the inter-array cable (the length between the turbine and the static section on the seabed). At Hywind Scotland Pilot Park, the dynamic section of the inter-array cable (distances F and G in Figure 25) extends 175 metres from the turbine substructure.

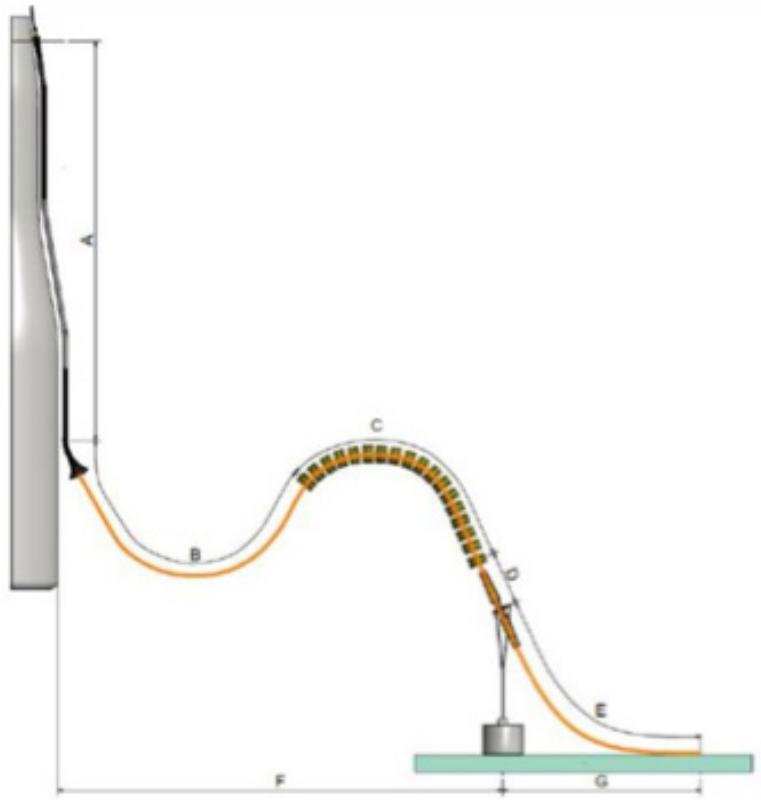


Figure 25: Hywind Scotland Pilot Park dynamic cable configuration (Statoil, 2016)

FOW farm developers may opt to bury the inter-array cables between their seabed touchdown points, though this decision will be made on a project-by-project basis. In deep water locations, mid-water cable configurations (whereby the inter-array cables do not touch the seabed) may offer economic advantages through reduced cable lengths. Such configurations would likely utilise buoyancy modules to create a cable arch midway in the water column, however this solution is unlikely to be required for FOW farms on the UK continental shelf.

It should be noted that, particularly in the case of catenary / free hanging and lazy wave configurations, the height that a given section of the cable occupies within the water column can be affected by platform motions (e.g. as the platform drifts towards and away from the seabed touchdown), and cables can drift laterally due to ocean currents. Furthermore, dynamic cables are susceptible to marine growth, particularly in the upper, warmer and more oxygenated, section of the water column. The effects of this can increase over time and impact a cable configuration due to the added mass of the system.

2.3.2 SUBSTATION

A typical commercial scale offshore wind farm will include an offshore substation that houses the wind farm's major high voltage power electronics. The turbines in the array are connected to the substation via their inter-array cables so that the inter-array voltage (33kV-66kV) can be transformed to a higher voltage (130kV-250kV) in order to minimise power losses during export to shore.

In deeper water sites (beyond the 100 metre limit), floating substructure concepts may offer a viable technical and economic solution to the developers of future commercial FOW farms. Floating substations remain a low TRL concept that is the focus of ongoing research projects, however it is believed that the substructure typologies being considered for FOW turbine applications (see Section 2.1) could be successfully adapted for floating substations.

Experience in the deployment of floating substations remains limited, though the Fukushima Kizuna demonstrator substation in Japan is a notable example. Installed in 2013, the prototype substation was deployed to step the output voltage from the project's prototype floating turbine from 22kV up to 66kV for export to shore. Installed on a spar platform concept, the substation's transformer system was subjected to vibration and inclination testing prior to deployment to establish its suitability for floating applications. The substation has been operational since installation and is scheduled for decommissioning in 2021.

The project has demonstrated that a substation's high voltage power electronics can, in principle, operate successfully while undergoing accelerations due to floating platform motions. However, further testing and qualification is required in order to scale up this technology from output voltages of 66kV to 250kV, and the economic case is yet to be proven in practice. Due to the smaller scale of early pilot projects such as Hywind Scotland and Kincardine Offshore Wind Farm, no offshore substations have yet been deployed at a UK FOW project.

Figure 26: Fukushima floating offshore substation (Fukushima Offshore Wind Consortium, n.d.)

2.3.3 DYNAMIC EXPORT CABLE

A wind farm's export cable connects the offshore substation to the onshore substation, where the voltage is transformed again to allow for connection to the mainland transmission network. Whilst there is a proven track record in the fabrication and deployment of export cables in the bottom-fixed wind sector, further technology developments are required to enable a dynamic export cable connection to future floating offshore substations.

In contrast to the wet designs of inter-array cables, the higher voltage of export cables (130kV-250kV) requires a dry design whereby a lead sheath is traditionally used to establish a radial water barrier. Such designs however have a poor fatigue life and are not suited to dynamic cable applications. Furthermore, some key auxiliary components, such as bend stiffeners, are not yet commercially available in the appropriate scale and with the relevant dynamic properties required for export purposes.

Following seabed touchdown, the export cable will typically be buried up to three metres below the seabed level for the remainder of its route to the landfall location. Rock placement may also be used along the export cable route if it is deemed necessary for additional protection, or if a sufficient burial depth cannot be achieved due to seabed conditions.

2.4 TURBINE

The early consensus within the industry is that, as the FOW industry commercialises, the wind turbines deployed on floating substructures will be technologically similar to those used in bottom-fixed offshore wind, with a limited number of key distinctions. For this reason, limited focus is devoted to turbine design here.

One area of difference is likely to relate to the turbine's control system, which will require bespoke developments in order to manage the impact of floating platform motions on power production and drivetrain fatigue life, and to avoid negative damping effects on the FOW substructure. Furthermore, changes to the turbine tower's stiffness may be required to minimise tower fatigue and to avoid resonances between the turbine's rotor frequency and the frequency of the floating platform's oscillations.

With full scale commercial FOW deployment targeted by 2030, it is likely that the turbines deployed will have grown significantly both in capacity and dimensions. Outlined below are indicative turbine dimensions based on installed capacity. For context, Hywind Scotland installed five 6MW Siemens SWT-6.0-154 turbines in 2017, while the Kincardine Offshore Wind Farm will install five Vestas V164 9.5 MW turbines between 2020 and 2021. Turbine capacities are expected to reach 12MW and 15MW within the next decade, with 20MW turbines considered technically feasible in the longer term.

In order to minimise inter-array wake loss effects and maximise annual power output, offshore wind turbines are, as a guide, typically installed a distance of five to seven rotor diameters apart.

Detail	Definition / Scope	Unit	6MW	9.5MW	12MW	15MW	20MW
Hub height	Height from mean sea level to rotor hub	Metres	100	110	135	150	168
Rotor diameter	Full rotor diameter (i.e. including blades and hub)	Metres	154	164	220	240	277
Deployment Date	Actual and estimated installation dates	Year	2017 (Hywind)	2021 (KOWL)	Mid-2020s	Early-2030s	Late-2030s

Table 9: Hub height and rotor dimensions for offshore wind turbines

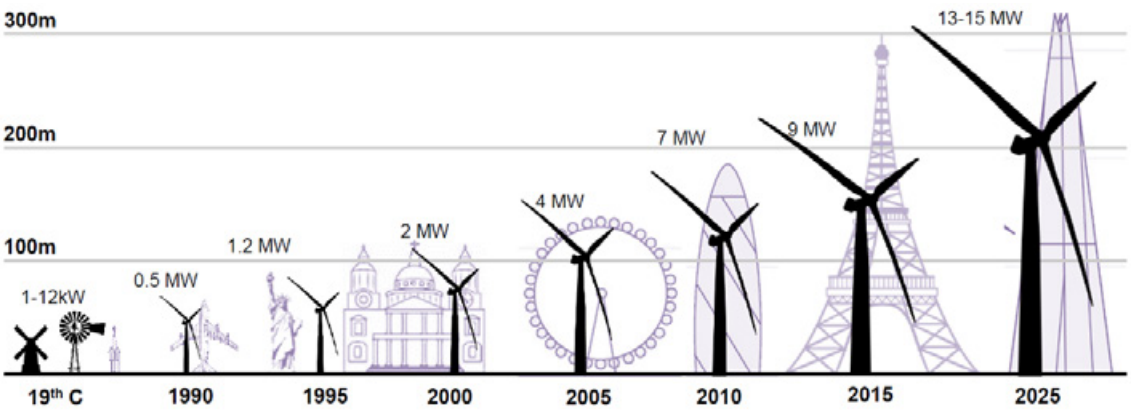


Figure 27: Evolution of wind turbine size and capacity (Bloomberg New Energy Finance, 2017)

3 MARINE OPERATIONS

A commercial FOW farm will have many of the same operational requirements as a bottom-fixed wind farm. Throughout a project's lifecycle, a FOW farm operator will undertake a planned schedule of inspection and maintenance activities, and they will also expect to perform a range of unplanned maintenance and repair tasks in response to component failures.

Despite the similarities, the maintenance of FOW turbines presents additional challenges beyond those faced in the bottom-fixed wind industry. The installation and/or exchange of major components at deep water sites will require heavy lift exchanges between floating platforms, therefore the additional relative motion will need to be mitigated. In principle, FOW turbines could be disconnected from their moorings and dynamic cables and towed to port in order to undertake certain maintenance activities, however the industry is still working to fully understand the logistical challenges and economic feasibility of this strategy. The installation process for commercial FOW farms may also differ significantly from that of bottom-fixed projects and developers will likely seek cost savings by bringing inshore as much of the substructure and turbine assembly process as possible.

The following subsections provide a high-level overview of the potential installation process and operational logistics of future commercial FOW farms.

3.1 ASSEMBLY AND INSTALLATION

In contrast to bottom-fixed wind, where a significant proportion of the wind farm's assembly and installation process (including foundation installation, turbine assembly, pre-commissioning tests) will take place offshore at the wind farm location, FOW provides the opportunity to bring many of these processes to inshore locations.

The precise installation procedure for a commercial FOW farm will depend on the substructure typology selected by the developer. As outlined in Section 2.1, the larger draft of spar designs means that deep water assembly sites will be required for turbine-substructure integration, while semi-submersible, barge and TLP designs offer a smaller draft that may allow developers to use port facilities with a standard water depth for platform load out and turbine installation.

3.1.1 MOORING INSTALLATION

A FOW farm's mooring systems may be installed up to a year in advance of the arrival of the turbines. Installation is likely to be conducted from an anchor handling vessel (AHV) with the support of a remotely operated underwater vehicle (ROV) and potentially also a guard vessel. Depending on the type of anchor utilised, additional support equipment may be required. For example, whilst a drag embedment anchor is relatively simple to install from an AHV, a suction pile anchor will likely need a specialised support crane for positional control, and a driven pile anchor will require a piling hammer to penetrate the seabed.

Once installed, the anchors and mooring lines will be left on the seabed until the FOW turbines arrive, and marker buoys may be used to mark out the mooring system locations. An average installation time of 8 hours per mooring line is expected.

3.1.2 SUBSTRUCTURE ASSEMBLY

A FOW farm's floating substructures will most likely be fabricated and assembled at a portside fabrication yard in order to enable ease of load out into the water ahead of the installation process. Depending on the capabilities of the local supply chain, developers may opt to fabricate the platform's key structural components at a specialised and/or commercially competitive site elsewhere in the region, or overseas, before transporting them to a facility closer to the wind farm location for final assembly.

A FOW project's assembly site will be selected based on a range of factors, including its proximity to the wind farm location, available laydown space, ground bearing capacity, crane access, and quayside length and draft. Whilst dry docks could in principle be used for the fabrication of smaller draft substructure designs, there may be a risk that this approach could create a bottleneck in the assembly process for commercial-scale FOW farms with dozens of turbines. Developers may instead opt for facilities that offer a greater quayside area that allows for multiple substructure assembly lines. It is anticipated that a manufacturing time of 7-15 days per substructure would be achievable for commercial FOW farms, if the appropriate assembly facilities are available.

Once assembled, the substructures will be loaded out, a process that will likely involve the use of SPMTs (self-propelled modular transport) to transfer the substructures from their quayside assembly point and onto a submersible barge for deployment into the water. The load out process will be simpler for semi-submersible and barge substructure designs due to their smaller draft and self-stable design. Spar substructures will likely be loaded out in a horizontal state and then transferred to a deeper water site where they can be ballasted and upended ahead of installation. Whilst TLP designs have a smaller draft, their reliance on their mooring system for stability means a specialist support vessel will be required during the load out and installation process.

Figure 28: Hywind spar assembly and load out (ALE, 2021) (Equinor, n.d.)

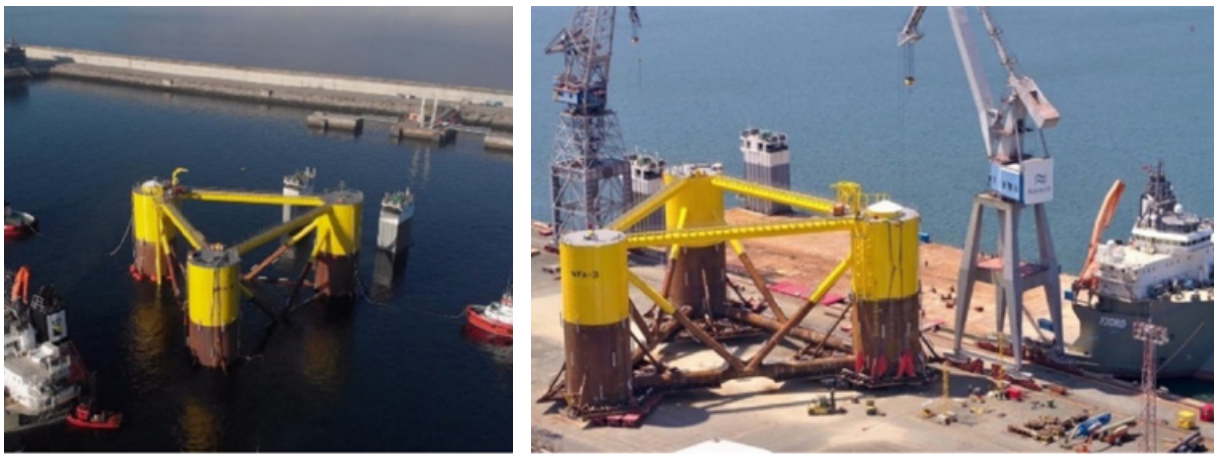


Figure 29: WindFloat semi-submersible assembly and load out (Wind Systems, 2019) (EDPR, 2019)

3.1.3 TURBINE INSTALLATION

Turbine installation will take place following the assembly and load out of the FOW substructures. In bottom-fixed wind, turbine installation would be conducted offshore at the wind farm location with the support of jack up vessels. However, FOW farm developers will be keen to develop a more cost-effective approach that does not rely on the use of the heavy lift dynamic positioning vessels required to install a turbine in a deep-water location.

Turbine OEMs (original equipment manufacturers) will typically deliver the main turbine components, including the tower sections, nacelle, rotor blades, to the assembly site ahead of the installation. If the quayside water depth is sufficient, small draft substructures can be moored against the quay and the turbine installed using an onshore crawler or ring crane. As a spar substructure will need to be upended in deeper water prior to the turbine installation, a deep-water heavy lift vessel will likely be required.

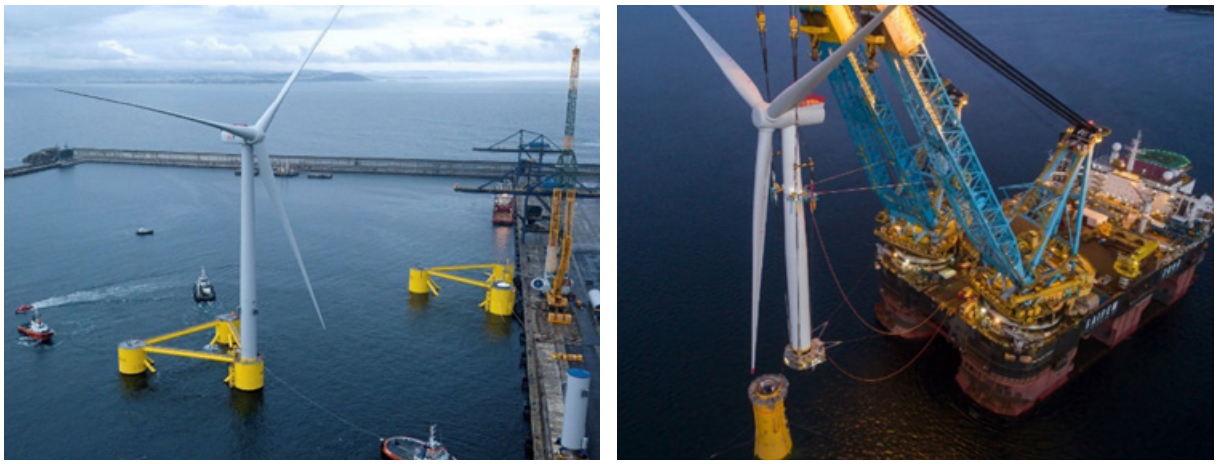


Figure 30: Turbine installation onto the Windfloat semi-submersible platform (L) and Hywind spar platform (R) (Recharge News, 2020) (Saipem, n.d.)

Once the turbine is installed on its substructure and has undergone pre-commissioning (anticipated to take 3 days per turbine), the integrated turbine-substructure system can be towed to the windfarm location and hooked-up to its mooring system. For self-stable substructure designs, the towing process will likely involve an AHV and two harbour tugs. Mooring stabilised substructure designs will require additional stabilisation support during transit, which is likely to be approached on a design-by-design basis. Depending on stability concerns, developers using TLP substructures may decide to install the turbines at site once the platform is connected to its moorings. Upon arrival, an AHV will retrieve the mooring system from the seabed for connection to the substructure. Again, the exact coupling mechanism between the substructure and its moorings will be on a design-by-design basis.

3.2 OPERATIONS AND MAINTENANCE

During a FOW farm's operational phase, an owner/operator will undertake a range of planned and unplanned inspection and maintenance tasks. Planned maintenance strategies will be driven in part by statutory requirements and also by a developer's drive to maximise a project's economic viability by striking a balance between the cost and benefits of inspection and maintenance work. Unplanned work will be undertaken in response to component failures or alarms triggered by the wind farm's monitoring systems.

3.2.1 SCHEDULED MAINTENANCE

An operator will aim to conduct planned inspection and maintenance activities during the summer months during which the typical wind speeds and wave heights are lower, thereby offering wider weather windows for accessing the turbines and minimising lost revenue due to turbine shutdown. Where issues are identified during the course of routine inspections, an operator may be required to undertake additional, unscheduled repairs (see 3.2.2).

Turbines

Scheduled maintenance relating to a FOW farm's turbines is expected to align closely with the requirements of a fixed-bottom wind farm. These activities can be expected to include:

- **Annual Maintenance** – A general service of the turbine undertaken once a year by a small team of technicians (likely 2-3) during which bolted connections are checked and torqued if required, lubrication systems are replenished, and a range of other planned tasks are performed.
- **Blade Inspections** – A visual external inspection of the turbine's rotor, likely to be performed at least every 2 years. Checking for blade erosion, cracks, evidence of lightning damage etc.; follow-up non-destructive testing (NDT) may be required if potential damage is suspected. Traditionally undertaken by a team of rope access technicians, though the use of drones/unmanned aerial vehicles (UAVs) for blade inspections is becoming increasingly common (UAV pilots are currently required to maintain visual line of sight with the drone during flight). Internal blade inspections and lightning protection system conductivity checks will also be performed, though potentially less frequently than external visual inspections.
- **Internal Nacelle System Inspections** – Visual inspection and potential NDT of the blade adjustment system, drivetrain components (including the gearbox, rotor bearings, rotor breaks), and generator (including bearings and electrical components). May be conducted alongside annual maintenance.
- **Turbine Electrical System Inspections** – Visual inspection and testing of the turbine's high-voltage electrical systems, including power converter, transformer, switchgear etc.
- **Statutory Inspections** – Annual inspection and certification of key safety and access systems including access ladders, anchor points, service lifts, turbine cranes, fire protection systems etc.

A turbine will be shut down for the majority of the activities outlined above. Depending on the FOW farm's distance from shore and the operator's chosen logistic strategy (see Section 3.2.3), transit to the turbine to perform these tasks will be via crew transfer vessel (CTV) or service operation vessel (SOV).

Substructure

FOW farm operators are required by regulation to inspect a floating substructure at least every 5 years. External visual substructure inspections will likely be conducted using an ROV deployed from a surface vessel (connected via an umbilical tether), as operators are seeking to mitigate the high-risk of diver-based inspections, while inspection of a substructure's internal compartments will be conducted by technicians.

The critical failure modes that operators will look to identify during inspections include:

- **Corrosion** – Applies particularly to the splash zone.
- **Fatigue** – Primarily due to wind and wave loading, but can be enhanced by resonance effects when the rotor frequency aligns with the structure's natural frequency.
- **Marine Growth** – Likely to accumulate on the submerged sections of the substructure during the course of the project's life. Can place the structure under additional stress due to the added weight.
- **Cracks** – Could compromise the platform's water tightness. May be of greater risk to FOW farms with concrete substructures.
- For substructures with active ballast systems, the internal pumps will be inspected for signs of wear or mechanical failure.

Mooring System

As with the substructure, FOW farm operators are required to inspect a turbine's mooring system at least every 5 years. ROVs will be used for the inspection of the underwater components (i.e. the vast majority of the mooring system, if not the entire system for some designs), with traditional diver-based methods avoided whenever possible. The particular failure modes that the inspections will look to identify will depend on the chosen mooring line material.

Chain:

- **Tension-Tension Fatigue** – Can cause fatigue cracks at and either side of a chain link's crowns.
- **Out-of-Plane Bending Fatigue** – A particular risk at the fairlead / chain stopper connection.
- **Corrosion** – Can affect the entire chain but is a particular risk in the upper section and splash zone.
- **Inter-Link Wear** – Impacts the contact points between chain links, reducing their diameter over time.
- Other mechanical damage can include installation damage and chain twists.

Synthetic Rope:

- **Mechanical Damage** – Can occur either at a wire's splice points, or along the body of the wire.
- **Internal Damage** – Currently difficult to detect with available technologies.

Wire Rope:

- **Fatigue** – May be evident on the surface of the wire, though visibility may be obscured if a protective coatings has been applied to the wire. Wire terminations may also be affected.
- **Corrosion** – Can affect the entire wire. Again, visibility may be obscured if a protective coatings has been applied to the wire.

Dynamic Cables

An offshore wind farm's array cables are a critical subsystem that are highly vulnerable to damage and which, to date, have been the leading cause of insurance pay-outs in the industry. The dynamic configuration of a FOW farm's array cables only increases this risk. As a result, a commercial FOW farm's dynamic cables will be subject to a close inspection and monitoring programme throughout their operational life. The frequency of inspection will be determined by the operator according to the expected performance of the cable system in response to the environmental conditions.

The planned inspection programme will focus on the following potential risks and failure mechanisms:

- The emergence of free cable spans, and the condition of any previous repairs made by the operator to fill in or support cable spans.
- Seabed scour, or cable damage caused by debris.
- Failure in the cable's armour or protective sheath.
- Accumulation of marine growth.
- Fatigue or damage to the bend stiffeners and in-line transition joints.

Monitoring systems will also be utilised to detect any changes in a cable's performance that may indicate damage or failure. This will include electrical parameters (voltage, current and power), a cable's temperature, as well as mechanical measurements to determine the static and dynamic loading at critical points in the system.

3.2.2 UNSCHEDULED MAINTENANCE AND TOW-TO-PORT VS IN-SITU REPAIRS

An operator will be required to undertake unscheduled maintenance as and when a component failure occurs, or damage is identified during the course of routine inspections. The operational requirements of unscheduled repair work will depend on the location of the fault (for instance, internal or external, above or below the water level), the size of the components involved and the scale of any lifting requirements.

A significant question facing the industry, and one to which the answer remains unclear, is the extent to which operators will opt to tow FOW turbines back to port to undertake major repair work, versus carrying out the work in-situ at the wind farm. Both strategies will be faced with technical challenges, and the economic case for adopting either approach is still uncertain. It is likely that an operator's decision to perform major repairs either in port or in-situ will be driven by substructure design. The smaller draft and natural stability of semi-submersible and barge designs might mean that they are better suited to tow-to-port strategies, as they are less likely to encounter challenges mid-journey due to seabed bathymetry and do not require complex or costly stability support. On the other hand, the larger draft of spar designs will prevent the platform from entering the majority of commercial ports (particularly in the UK), while a TLP platform's instability when disconnected from its moorings will mean that it will require stability support during transit.

Key considerations for a tow-to-port strategy include:

- **Weather** – A suitable weather window is required for the duration of the disconnection and towing process. Disconnecting the turbine from its moorings and dynamic cables can take up to 3 days, while the duration of the towing process will depend on the distance between the wind farm and the port (with a towing speed of 2 to 3 knots expected).
- **Navigation** – The relevant licences will need to be obtained from the Maritime and Coastguard Agency for the towing operation, and a notice to mariners should be issued. Compliance with international standards on navigational lights will be required. An operator may opt to tow the turbine outside of the main navigational channels in order to minimise interactions with other vessels.
- **Mooring System** – The efficiency of the process will depend on the whether the coupling mechanism between the mooring system and substructure is well suited to disconnection and reconnection. There may be a trade-off between the ease of disconnection and the robustness of the system, particularly in respect of corrosion and marine growth. During disconnection, chain mooring lines could be wet stored on the seabed. However, synthetic and steel wire are more liable to abrasion when in contact with the seabed, and so a temporary buoy may be required to keep them suspended in the water column.
- **Dynamic Cables** – During disconnection, dry-mate connectors must be sealed to prevent seawater ingress. For future commercial FOW farms, specialised buoyancy modules with connector terminals may be developed to provide the dual function of keeping disconnected cables suspended in the water column and maintaining an inter-array electrical connection whilst a turbine is removed.
- **Port Access** – The availability of suitable port facilities (that has the required draft, availability, crane capacity, access channel etc.) within towing distance is a key consideration for any tow-to-port procedure.

In-situ repairs on the other hand present alternative challenges:

- **Offshore Component Exchange** – The exchange of major components (blades, drivetrain components, HV electrical systems etc.) on FOW turbines presents significant additional challenges. Whilst bottom-fixed turbines are secured fast to the seabed and are located in water depths that are suitable for jack up vessels (thereby largely eliminating relative motion between the turbine and the vessel), FOW turbines are continually subject to floating platform motions. Additionally, in deeper water sites beyond the reach of jack up vessels, floating heavy lift vessels will need to be used, thereby increasing the relative motion between the turbine and vessel. Motion compensation solutions are a current area of innovation, but do not yet meet the requirements of the FOW industry.
- **Vessel Availability** – As it stands, the current heavy lift vessel market would not meet the requirements of a commercial scale pipeline of future FOW farms. Furthermore, the next generation of offshore turbines (i.e. 15MW, and potentially even 20MW) will be beyond the physical reach of current heavy lift vessels. There is therefore a demand for a new generation of deep water heavy lift vessels, and it remains to be seen whether there will be sufficient availability of these vessels by the early 2030s.
- **Weather** – As with tow-to-port procedures, in-situ repairs are also sensitive to weather conditions. Whilst the duration of the required weather window may not be as long for in-situ repairs, the feasibility of floating-to-floating component exchange is dependent on the appropriate sea state, and both the significant wave height and wave period will need to be carefully evaluated.

When major repairs are required on future commercial FOW farms, an operator's decision to tow a turbine to port or perform the task in-situ based will ultimately be based on economic decisions that factor in the cost of insurance, the difference in lost revenue incurred through each approach, the difference in vessel cost between offshore heavy lift vessels versus AHVs and tugs, port pilotage costs, and a number of other factors.

As inspection and monitoring techniques develop and improve, developers will seek as far as possible to shift their efforts from unscheduled activities to planned maintenance. By performing more minor, preventative maintenance tasks based on the outputs and predictions of advanced structural health and condition-based monitoring systems, operators will hope to unlock cost savings by preventing major failures later in the project's lifecycle.

3.2.3 LOGISTICS STRATEGIES

Two fundamental logistics strategies are available for providing access to FOW farms: CTV-based, and SOV-based.

- **CTV Logistics Strategy** – Currently the most common approach used by UK offshore wind farms today and involves the use of a fleet of smaller crew transfer vessels (CTVs) for the transit of technicians between an onshore operations and maintenance (O&M) base and the offshore wind turbines. CTVs can be hired on short term charter in response to the level of maintenance required during a given period and are well-suited to wind farms that are closer to shore (e.g., less than 2 hours from port) and with less energetic average sea states. Turbine access via a CTV is typically limited to significant wave heights of less than 1.5 metres. CTV sizes vary and can usually accommodate between 12 and 24 technicians per trip.
- **SOV Logistics Strategy** – As wind farms are developed further from shore and transit times to port increase, the use of service operation vessels (SOVs) becomes more viable. SOVs are much larger than CTVs and can serve as offshore accommodation vessels for a wind farm's technicians. An operator will likely only hire one SOV per wind farm and will do so on a longer-term charter (e.g., up to 10 years). A typical SOV might have the capacity to accommodate around 60 technicians at a given time and may remain within the wind farm for intervals of a fortnight. For wind farms that are further from shore (for example, more than 50km), the use of an SOV will cut down transit time and enable technicians to spend a greater portion of their shift performing maintenance tasks on site. Furthermore, SOVs are normally equipped with a motion compensated gangway, or "Walk-2-Work" system, that enables technicians to access turbines in significant wave heights of up to 3 metres, thereby widening the weather windows for turbine access.

As commercial FOW farms are likely to be built further from shore where the environmental conditions will be more challenging, operators might increasingly favour SOV logistics strategies ahead of the CTV-based alternative.

4 GEOGRAPHICAL DISTRIBUTION

4.1 FOW DEVELOPMENT CONSTRAINTS

The geographical distribution of future commercial FOW projects will depend on a range of constraints that determine which areas of the sea are suitable for the deployment of FOW farms. These constraints range in nature from hard technical limits, through to social, practical, and environmental considerations. Whilst these constraints can be categorised into a range of taxonomies, broadly speaking they include:

- **Environmental** – Bathymetry; seabed sediment; wind and wave resource.
- **Stakeholders and Other Sea Users** – Fishing industry; navigation; aviation; radar; leisure industry.
- **Infrastructure** – Proximity to fabrication yards and O&M facilities; presence of O&G platforms, pipelines and leasing areas; presence of other offshore wind farm; subsea power lines, including grid network and export cables; telecommunication lines; shipwrecks and unexploded ordinance.
- **Conservation** – Marine Protected Areas (MPAs), Special Protected Areas (SPAs); Special Areas of Conservation (SACs); other wildlife impacts, including birds, marine mammals, fish and benthic ecology; visual impacts.

While a site may be suitable for FOW development based on the above parameters, a developer will still need to perform an economic assessment of a prospective FOW farm development in order to determine its commercial viability.

The view of the Floating Offshore Wind Centre of Excellence is that, in the medium term, it is likely that the majority of early commercial FOW projects will be installed in water depths of 75-150 metres, while in the longer term, further cost reductions for FOW will enable greater exploitation of water depths outside of the 75-150 metre range.

4.2 OFFSHORE WIND DEPLOYMENT IN SCOTLAND

In October 2020, Marine Scotland published its Sectoral Marine Plan (SMP) for Offshore Wind Energy. The SMP was developed through an iterative scoping, consultation, and assessment process. Draft "areas of search" were initially proposed and then reviewed and revised through a series of stakeholder engagements as well as a social, economic, and strategic environmental assessment (and habitat regulation appraisals) process. Based on the outputs of this development process, the SMP set out a series of final Plan Options that are deemed to be the most suitable and sustainable locations for the development of future offshore wind farms in Scottish waters. (A draft version of the SMP had previously been published in 2019 outlining the Draft Plan Options.)

The 15 Plan Options, which have been grouped into four general regions – West (W), North (N), North East (NE), and East (E) – are outlined in Figure 31. Due to the range of site parameters featured across these sites, the Plan Options represent potential opportunities for both fixed and floating offshore wind developments.

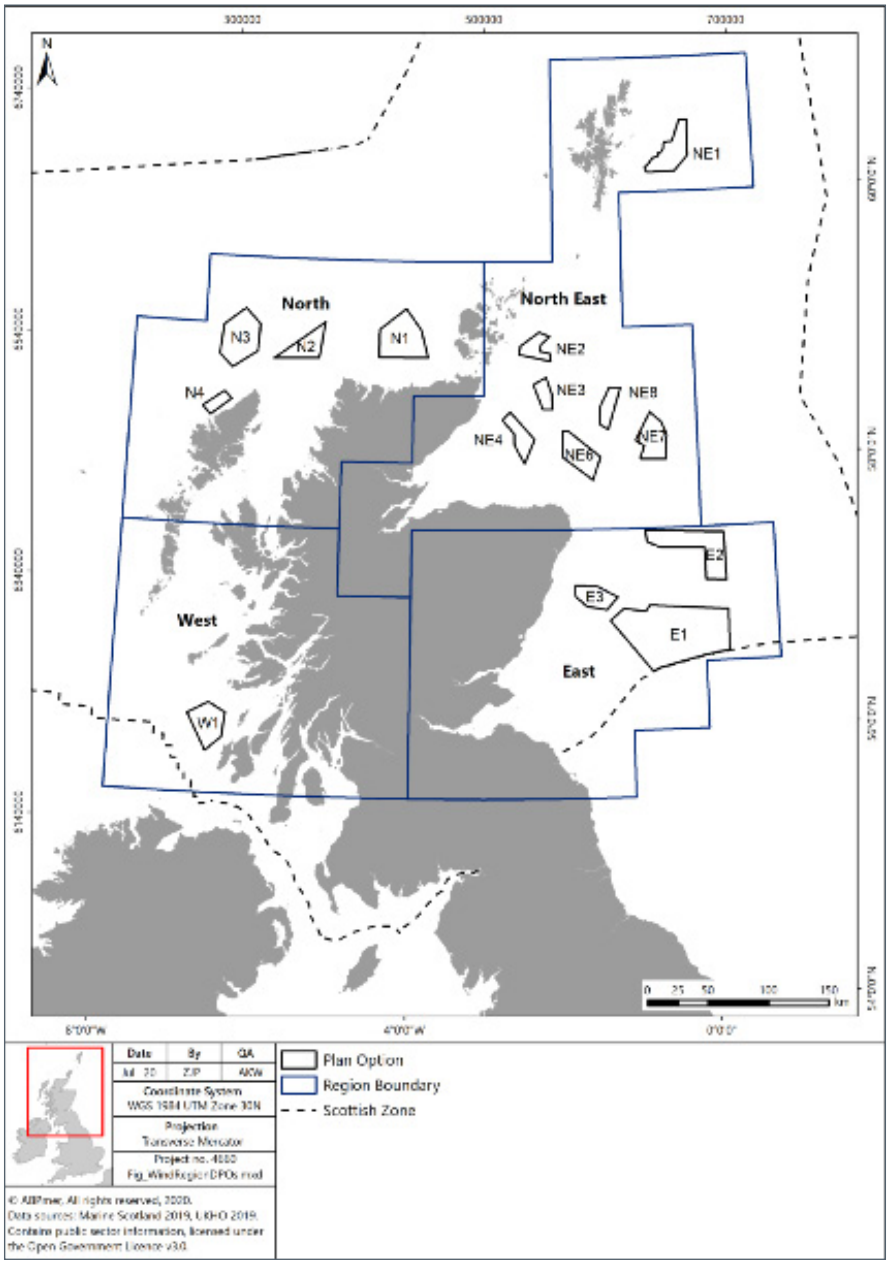


Figure 31: Sectoral Marine Plan for Offshore Wind Energy – Final Plan Options (Scottish Government, 2020)

Crown Estate Scotland (CES) is responsible for granting seabed leases to offshore wind farm developers in Scotland. In June 2020, CES launched the ScotWind Leasing round – the first round of offshore wind leasing in Scottish waters in a decade. The ScotWind Leasing round invites developers to apply for an Option Agreement for a wind farm development located within the Plan Options set out in the SMP. Developers who are awarded an Option Agreement for a given area of the seabed will be permitted to begin site investigations and preparing a consenting application, with the ultimate aim of obtaining a seabed lease.

The Floating Offshore Wind Centre of Excellence has undertaken a GIS modelling exercise to determine, based on a range of site parameters (see Section 4.1), which of the SMP Plan Options might be best suited for FOW developments. This initial desk-based review concluded that, of the SMP Plan Options, sites **NE1**, **NE7** and **NE8** presented strong cost reduction opportunities for early FOW developments (though it should be stressed that other sites suitable for FOW deployment are also expected to be developed in due course).

5 LIFECYCLE

5.1 LIFECYCLE PHASES

A commercial FOW farm will progress through the same general lifecycle phases as a fixed bottom offshore wind farm. These can be broadly categorised as follows:

5.1.1 DEVELOPMENT

The development phase encompasses all of the activities that a developer undertakes before taking a final investment decision to proceed with the construction of a wind farm. Development phase of an offshore wind farm can typically take between 4 to 6 years and will cover the design and engineering of a wind farm as well as the steps required to obtain planning consents. A design envelope approach will usually be adopted in order to provide the developer with greater flexibility at the consenting stage (by including ranges of design parameters, rather than committing to an exact design). Key steps include:

- Front end engineering and design (FEED) studies to define the initial design characteristics of a wind farm, including array layout, substructure and mooring selection, electrical design, and operational planning
- An Environmental Impact Assessment (EIA) that assesses the potential impact of the wind farm on the natural and human environment throughout the project's lifecycle.
- Environmental surveys that provide a baseline for the EIA in relation to birds, marine mammals, fish, benthic ecology as well as human activities and key stakeholders.
- Resource assessments, conducted over the course of at least one year, based on the deployment of met masts, metocean buoys, as well as lidar and wave radar.
- Geological and hydrographic surveys to assess the seabed bathymetry, soil and rock strata, as well as a site's sedimentation and scour characteristics.
- Following the FEED and a successful consenting process, a developer is able to proceed with the final design, procurement and contracting processes ahead of the wind farm's construction.

5.1.2 CONSTRUCTION

The construction phase will commence once a wind farm has been designed and consented, awarded a seabed lease and generating contract, and has successfully secured financing.

This stage includes the manufacture and installation processes, and can normally take up to 2 years. See Section 3.1 for further detail on the assembly and installation process for commercial FOW farms.

5.1.3 OPERATION AND MAINTENANCE

Once it has been commissioned, a wind farm enters the operation and maintenance phase (O&M). FOW farm operators will hope to achieve an operational lifespan of at least 25 years in order to maximise the revenue from their generating asset. See Section 3.2 for more detail on the activities conducted during a FOW farm's O&M phase.

5.1.4 DECOMMISSIONING

Beyond the removal of small-scale demonstrator units at the conclusion of research projects, there is currently very limited experience in the decommissioning of FOW turbines. It is likely that a FOW farm's decommissioning process will closely resemble the steps involved during the tow-to-port process (see Section 3.2.2), but in reverse and at a wind farm-wide scale.

6 PORT REQUIREMENTS

The port requirements of a FOW farm will vary depending on whether the wind farm is in its construction or operational phase, as well as the owner's chosen maintenance and logistics strategy. High level considerations regarding a FOW farm's port requirements are outlined in the following subsections.

6.1 CONSTRUCTION PHASE

A FOW farm's port requirements will be more demanding during the construction phase, and developers will utilise facilities that have the capacity to handle substructure assembly and wind turbine staging. When selecting a construction port, a FOW farm developer will consider sites that are typically used as fabrication yards or marshalling and assembly ports. The main processes that will be conducted in port during the construction phase include:

- **Substructure Manufacture and Assembly** – Requires sufficient laydown space to hold the main components and to run parallel substructure assembly lines. Developer will have strict requirements regarding quayside ground bearing capacity, as well as quay length and draft. Available crane capacity is a key factor in a port's suitability. The extent to which substructure components are fabricated locally remains to be seen. Depending on the local supply chain's capacity and competitiveness, the main structural sections might be fabricated overseas and imported prior to assembly.
- **Turbine Staging** – Turbine components will be delivered to the assembly port by sea directly from the turbine OEM's fabrication facility. For FOW farm installation, turbines will likely be assembled and installed onto the substructure at the assembly port before being towed to the wind farm. The turbine's dynamic cables are likely to be installed directly from the turbine OEM's facility.
- **Mooring Staging** – The anchors and mooring chains or wires may be held at the assembly port for a period before being loaded onto AHVs and taken to the wind farm location for installation.

Based on the capacity of the facilities that are currently available in Scotland and the UK, and depending on the extent to which a FOW farm's components are fabricated locally (see Section 7.6 for an overview on local content targets), it is likely that a commercial FOW project will need to utilise multiple ports during the construction phase. Crown Estate Scotland recently conducted a review of Scotland's port capability and identified a number of ports that could potentially be utilised for offshore wind construction (see Figure 32). Note that this review pertains to both fixed and floating offshore wind, therefore some of the sites identified will not meet the requirements of a FOW developer.

The potential development of major "hub" ports that are able to deliver all of the manufacturing, marshalling and assembly functions within one facility has been discussed as a potential solution for supporting the future commercialisation of the offshore wind sector. To date, no such facilities exist either within Scotland or the UK, therefore the use of multiple ports for the construction of a FOW farm appears highly likely at least in the medium term.

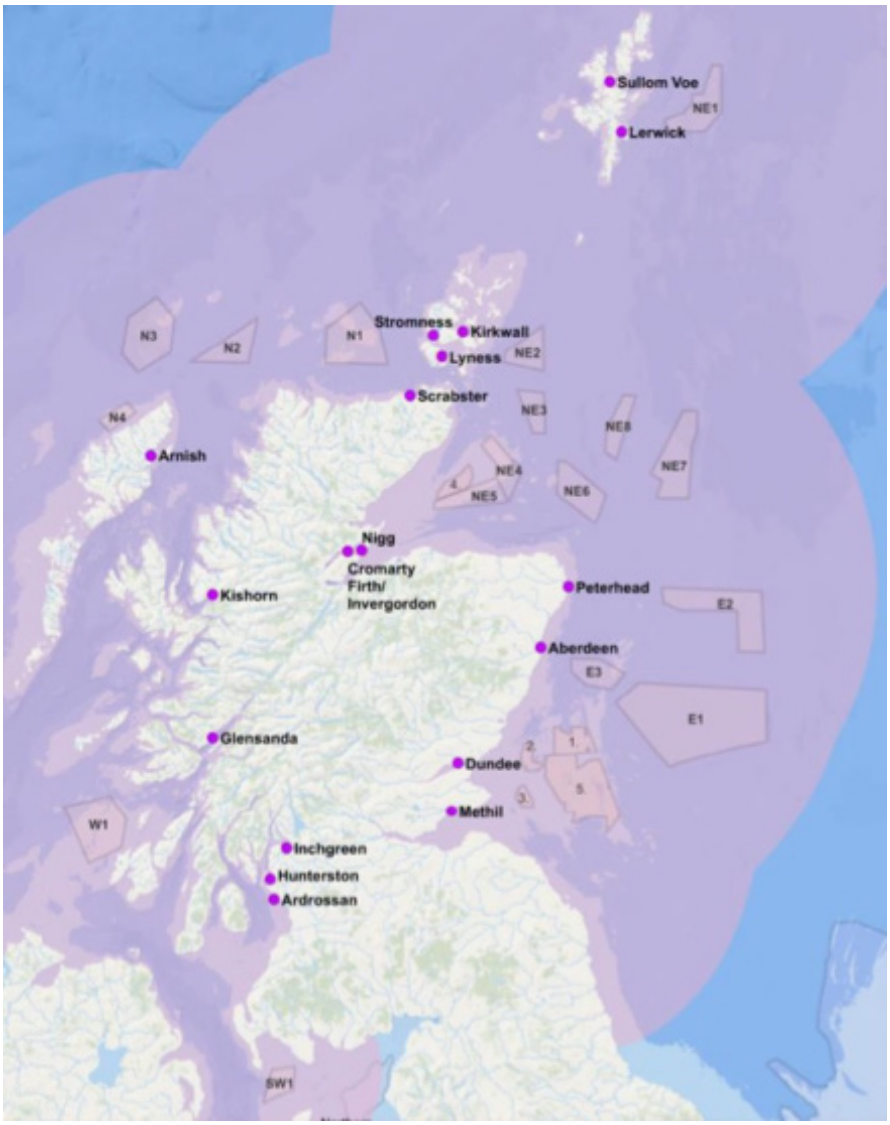


Figure 32: Scottish marshalling and assembly ports (200km sailing distance outlined) (Arup, 2020)

Figure 33: Nigg Energy Park, which was used as the foundations staging port for the Moray East (fixed bottom) offshore wind farm (Nigg Energy Park, 2020)

6.2 OPERATION PHASE

A FOW farm's port requirements during the operational phase will depend on a couple of key considerations, namely whether the owner opts for a CTV- or SOV-based logistics strategy, and whether they adopt a tow-to-port or in-situ approach to major repairs. Crown Estate Scotland's port review identified a range of ports in Scotland that could potentially be used as offshore wind O&M ports, depending on whether a CTV or SOV logistics strategy is selected (see Figure 34).

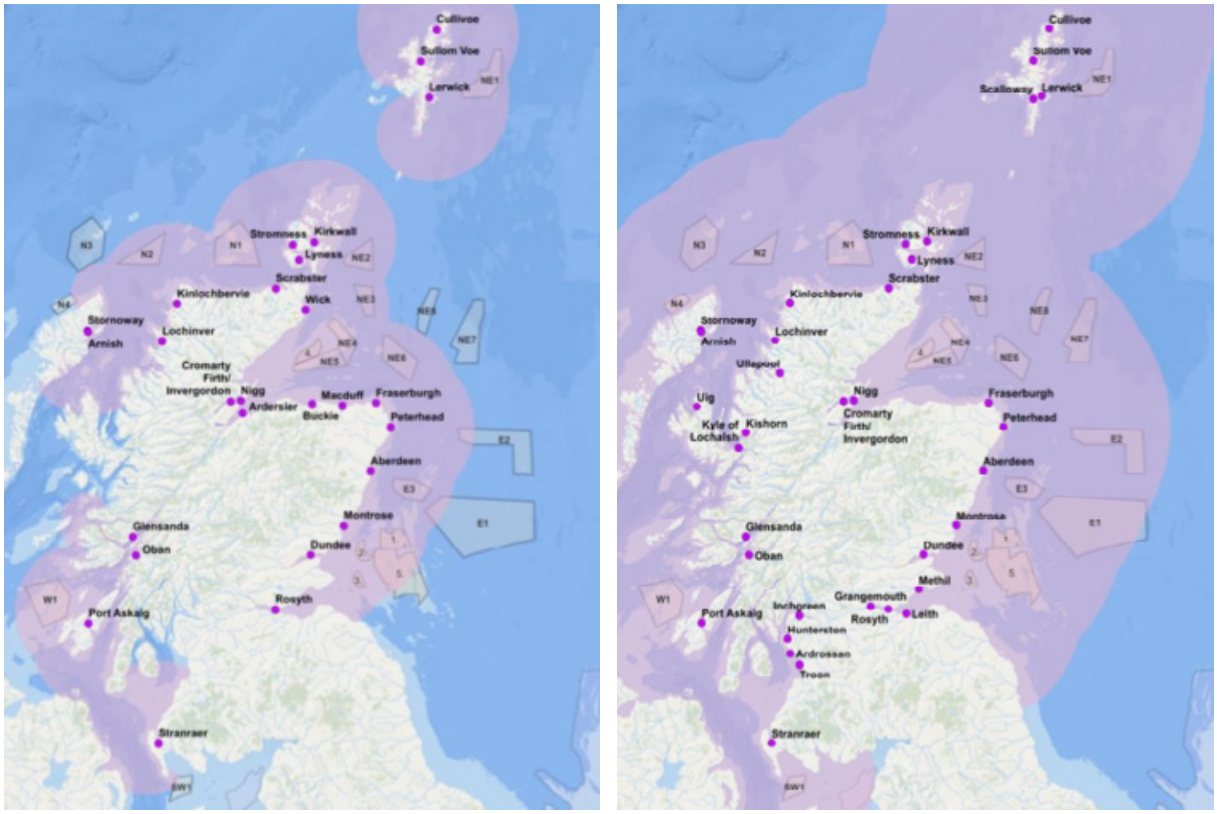


Figure 34: Scottish O&M ports (L: CTV 75km sailing distance; R: SOV 150km sailing distance) (Arup, 2020)

If a CTV-logistics strategy is adopted, then an O&M base will be used for the regular transit of technicians between the onshore base and the wind farm. However, if a developer opts for an SOV-logistics strategy, then the technicians will be based at the wind farm for durations of up to a fortnight, and fewer trips to the O&M port will be required. Where an SOV strategy is adopted, minor adaptations may be required at the port (such as the addition of a pontoon quay) to account for the larger draft of the SOV.

If a FOW farm's major repairs are conducted in-situ at the wind farm location, then a developer's requirements of the O&M base will be less extensive. However, in the case of tow-to-port maintenance strategies, the O&M base will be required to temporarily accommodate the disconnected FOW turbine. The additional restrictions that this places on quayside length, water depth and crane capacity will rule out many of the O&M bases that would otherwise be considered. As a result, there is likely to be greater overlap with the ports considered for a FOW farm's construction phase, and those that might be used for tow-to-port maintenance strategies.

Figure 35: Port of Peterhead, which is used as the O&M base for Hywind Scotland Pilot Park (Peterhead Port Authority, 2021)

7 COMMERCIAL DRIVERS

7.1 UK OFFSHORE WIND TARGETS

At a national level, governments and public bodies can announce their support for FOW development by setting out targets for sectoral growth. Whilst not legally binding, the purpose of such targets is to instil confidence amongst FOW developers and their prospective lenders.

In an announcement in October 2020, the UK Government stated its commitment to securing 40GW of offshore wind by 2030 and set out a new, FOW-specific target of 1GW installed capacity by the same year. In the same month, the Scottish Government announced an ambition of 11 GW of installed offshore wind capacity by 2030, though they did not include a specific target for FOW.

These targets are often revised in response to renewed ambition to meet climate change targets. For example, the recent UK and Scottish targets of 40GW and 11GW each represented an increase on previous 30GW and 8GW targets and ambitions, respectively.

Also of relevance is the Committee on Climate Change (CCC)'s target for offshore wind deployment. The CCC is a non-departmental public body that advises the UK Government on its climate change and net zero strategy. In 2019, the CCC recommended that the UK will require 75GW of offshore wind deployment by 2050 in order to meet its legally-binding net-zero obligations.

7.2 CONTRACTS FOR DIFFERENCE

Whist announcements of growth targets can signify ambitions for the sector, the UK Government's principal support mechanism for offshore wind is the Contracts for Difference scheme. Contracts for Difference (CfDs), which are allocated through a series of auctions, or allocation rounds, provide developers with a guaranteed 'strike price' (in pounds per megawatt-hour, or £/MWh) for the first 15 years of their project's power output. This system provides wind farm developers and their lenders with the stability required to commit to a financial investment decision. CfDs have now replaced previous subsidy mechanisms for new renewable energy projects, such as renewable obligation certificates (ROCs).

Under the CfD scheme, the revenue available for a given generating technology is ringfenced into a series of 'pots' which prevent innovative generating projects from having to compete against more commercially mature technologies. The pot structure for the upcoming fourth allocation round is as follows:

- **Pot 1** – Established technologies, including onshore wind and solar PV.
- **Pot 2** – Less established technologies, including wave, tidal, biomass and floating offshore wind.
- **Pot 3** – Offshore wind.

This pot structure has been designed to give FOW and other innovative technologies the opportunity to establish early commercial projects without bidding against cheaper alternatives, such as bottom-fixed wind. In the two previous CfD rounds the cost of bottom-fixed has fallen from a low of £57.50/MWh in 2017 to a low of £39.65/MWh in 2019, meaning it is now cheaper than the wholesale market price of electricity. As a pre-commercial technology, FOW is not yet in a position to compete against these prices, hence the importance of the definition for Pot 2 in the technology's route to commercialisation.

7.3 COST OF ELECTRICITY DRIVERS

The cost of offshore wind (both fixed and floating) is measured in terms of its levelised cost of electricity (LCoE). The International Energy Agency (IEA)'s methodology for calculating LCoE is commonly used and can be characterised:

$$LCoE = \frac{\sum [(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t) * (1 + r)^{-t}]}{\sum [kWh_t * (1 + r)^{-t}]}$$

Where:

$Capital_t$ = total capital construction costs in year t;

$O\&M_t$ = operation and maintenance costs in year t;

$Fuel_t$ = fuel costs in year t;

$Carbon_t$ = carbon costs in year t;

D_t = decommissioning and waste management costs in year t;

$(1 + r)^{-t}$ = the discount factor for year t;

kWh_t = electricity generated in year t.

The lower a FOW project's projected LCoE, the more likely a developer is to secure a generating contract at a CfD auction round. Therefore, in any given year of a FOW project's lifecycle, FOW developers are incentivised to minimise the numerator of the LCoE calculation by keeping down capital and operational expenditure as much as is reasonably possible, while maximising the denominator by keeping the wind farm's power output as high as possible. Over the course of the next decade, technology innovation and research will have an important role to play in ensuring that the cost of FOW falls faster than it would under a "business as usual" scenario (where less emphasis is placed on innovation).

As operational experience grows and the FOW industry is gradually perceived by lenders as less risky, developers can also expect the cost of borrowing to fall. The weighted average cost of capital (WACC) for a FOW farm will depend in part on the perceived investability of the technology, therefore developers will be keen to avoid undue risks that might damage these perceptions.

7.4 OPERATIONAL FACTORS

A key indicator of a wind farm's performance that operators will monitor closely is a project's capacity factor. Capacity factor is the ratio of a project's power output over a given period to the maximum possible power output during that period. For a given project, it is often presented as the average ratio over the course of a year. For example, if an offshore wind farm with a total installed capacity of 500MW operated at an average output of 250MW over the course of the year, then its capacity factor would be calculated at 50%. A wind farm's LCoE is highly sensitive to its capacity factor, therefore FOW developers will be looking to boost this parameter as far as possible.

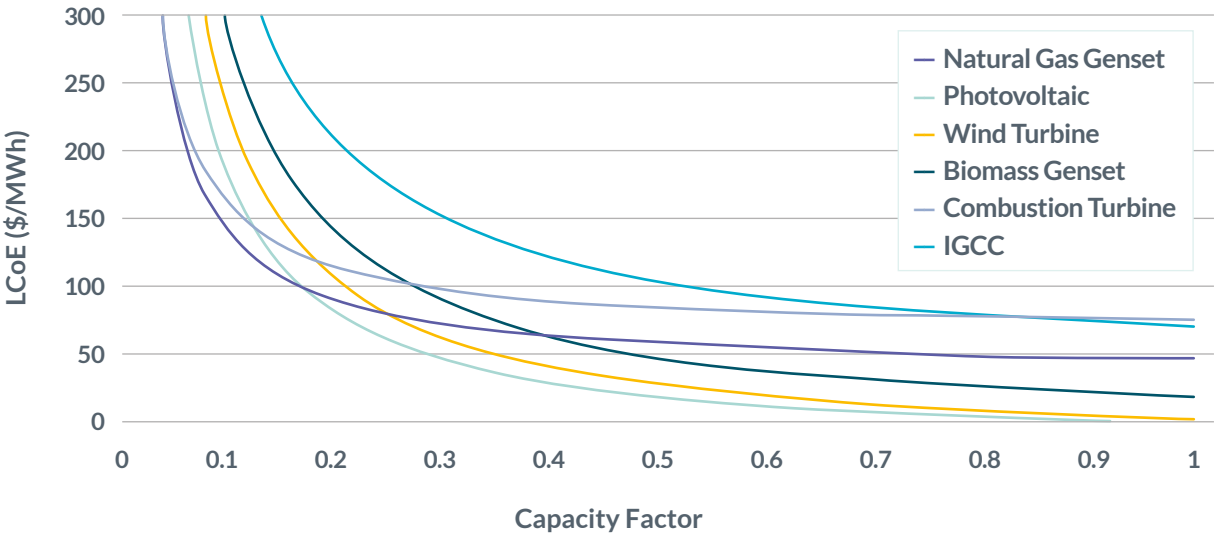


Figure 36: Indicative LCoE figures vs capacity factor for a range of generating technologies (C. Yuan, 2017)

The seasonal variation of wind speeds has a significant impact on the capacity factor for any given month in the year. A wind farm's power output is proportional to the cube of the windspeed (meaning a doubling of wind speed will lead to an eightfold increase in power generation). Operators will therefore aim to schedule planned maintenance for the summer months when wind speeds are lower and the sites are more accessible, thereby minimising turbine downtime during the windier, more profitable winter months.

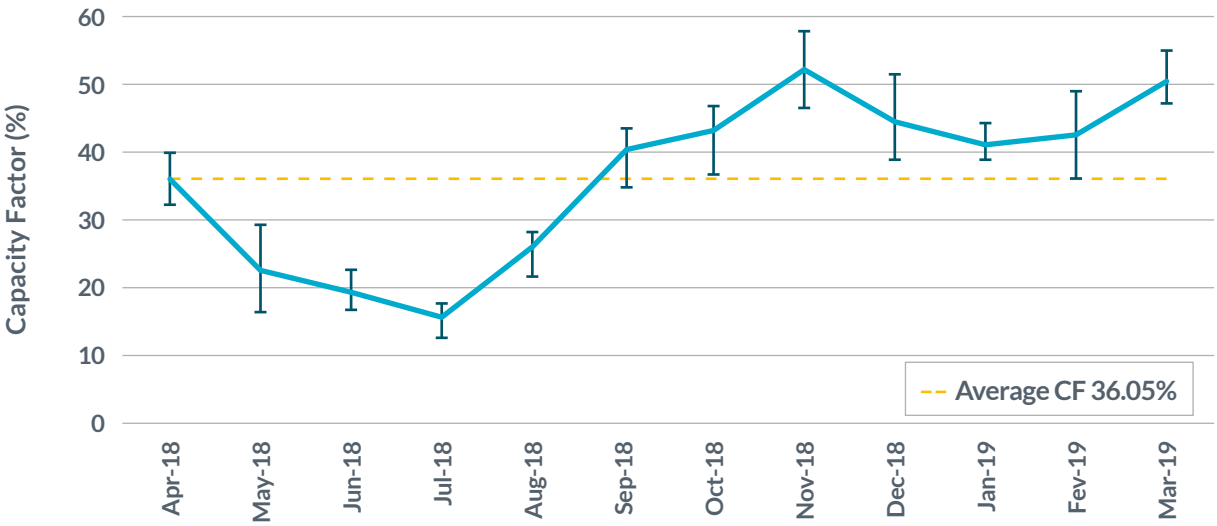


Figure 37: Average offshore wind capacity factors for UK offshore wind farms during 2018-19 (ORE Catapult, 2019)

Due to its sensitivity to wind speed, a wind farm's capacity factor is partly beyond the control of the wind farm operator. Therefore, an additional parameter that is useful to monitor is production based availability (PBA), which is a measure of a wind farm's output during a given period relative to the wind speeds available during that period. Whilst recent offshore wind annual capacity factors in the UK have averaged at 36%, Figure 38 shows that operators will aim for PBA values of over 95% for the majority of the year (with the exception of busy maintenance periods during the summer). An additional factor that may impact a wind farm's PBA during the winter months is that whilst the wind speeds enable a higher power output, if any faults or component failures occur, an operator may need to wait longer for a suitable weather window to perform the necessary repairs, leading to longer downtime periods in the interim.

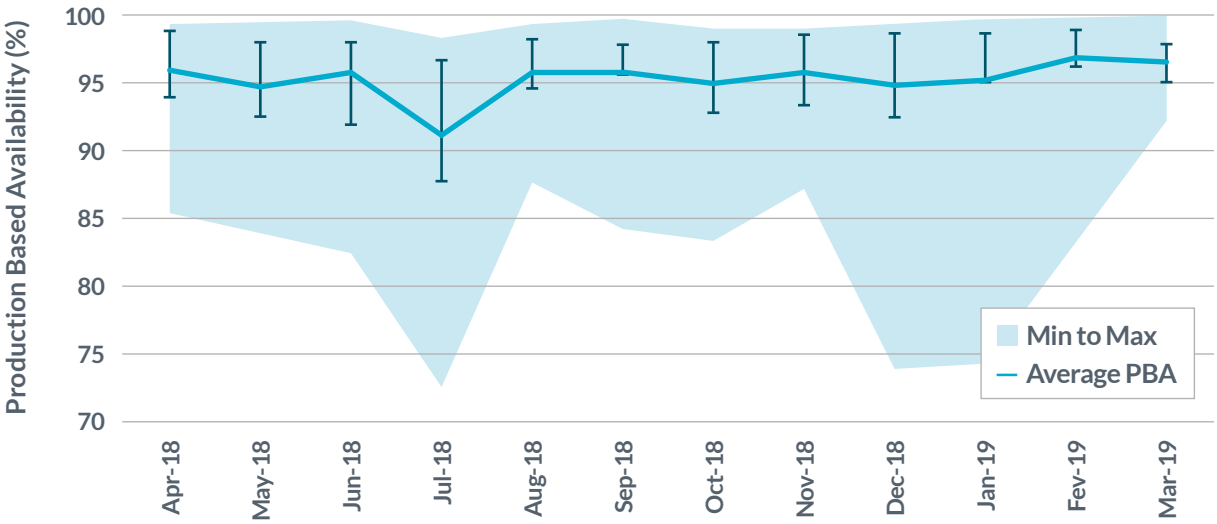


Figure 38: Production based availability (average and min-to-max) for UK offshore wind farms during 2018-19 (ORE Catapult, 2019)

Whilst limited data is available regarding FOW capacity factors, it is hoped that the ability to develop projects in deeper waters, further from shore, where the wind resource is stronger, will enable commercial FOW farms to achieve higher capacity factors than equivalent fixed bottom sites. The most relevant example available to date is the Hywind Scotland Pilot Farm, which is reported to have achieved an average capacity factor of 56% during its first two years of operation.

7.5 ECONOMIES OF SCALE

A healthy pipeline of commercial FOW projects is considered key to enabling future cost reductions for FOW. Higher, more consistent annual deployment rates will help to avoid a stop-start business model for the FOW supply chain. This, in turn, is expected to encourage investment in local FOW industry services, thereby improving the capability and efficiency of the supply chain organisations supporting a FOW project throughout its lifecycle.

Initial analysis conducted by the Floating Offshore Wind Centre of Excellence concluded that if the UK was to increase its offshore wind deployment target to 100GW by 2050, then, by 2030, the LCoE of FOW would be 20% lower than under the current 75GW by 2050 deployment target (set by the CCC).

7.6 SUPPLY CHAIN CAPABILITY

Under the Offshore Wind Sector Deal agreed between the UK Government and offshore wind industry in 2019, the sector committed to increase local content in offshore wind targets to 60% by 2030, including capital expenditure. As this commitment also applies to future FOW farms, there is a need to invest in and upscale the capabilities of the UK supply chain. There are significant gaps between the current number of supply chain companies with the capabilities required to support the FOW industry and the number of companies required to deliver anticipated deployment levels in the 2030s and beyond. This is particularly the case with regards to the manufacture of the key FOW subsystems, including substructures, mooring systems and dynamic cables.

The supply chain is a broad topic that presents important challenges to the offshore wind industry, both fixed and floating. For a more detailed overview of these challenges, see the Whitmarsh Martin Whitmarsh review on the UK Offshore Wind Supply Chain (Whitmarsh, et al., 2019) and the summary of the Offshore Wind Sector Deal (BEIS, 2019).

8 REFERENCES

ALE, 2021. *Weighing, Transportation and Load-Out of Five Spars for the Hywind Project*, Spain. [Online] Available at: **https://www.ale-heavylift.com/knowledge-centre/case-studies/weighing-transportation-and-load-out-of-five-spars-for-the-hywind-project-spain/** [Accessed 11 01 2021].

Arup, 2020. *Ports for offshore wind: A review of the net-zero opportunity for ports in Scotland*, Edinburgh: Crown Estate Scotland.

BEIS, 2019. *Industrial Strategy: Offshore Wind Sector Deal*, London: UK Government.

Bloomberg New Energy Finance, 2017. *London Summit 2017, Breaking Clean*. London, Bloomberg.

Borg, M. et al., 2020. Technical Definition of the TetraSpar Demonstrator Floating Wind Turbine Foundation. *Energies*, 13(4911).

C. Yuan, G. L. Z. W. X. C. a. M. S. I., 2017. Economic Power Capacity Design of Distributed Energy Resources for Reliable Community Microgrids. *Energy Procedia*, Volume 142, pp. 2561-2567.

Davidson, J. & Ringwood, J. V., 2017. Mathematical Modelling of Mooring Systems for Wave Energy Converters – A Review. *Energies*, Volume 10.

EDP, n.d. *Library*. [Online] Available at: **https://www.environdec.com/library?Epd=10437** [Accessed 08 01 2021].

EDPR, 2019. *Turbine assembly begins for the WindFloat Atlantic project*. [Online] Available at: **https://www.edpr.com/en/news/2019/07/17/turbine-assembly-begins-windfloat-atlantic-project** [Accessed 11 01 2021].

Equinor, 2021. *How Hywind works*. [Online] Available at: **https://www.equinor.com/en/what-we-do/floating-wind/how-hywind-works.html** [Accessed 05 01 2021].

Equinor, n.d. *How can an oil company be best at offshore wind?*. [Online] Available at: **https://www.equinor.com/en/magazine/hywind-oil-industry-expertise.html** [Accessed 11 01 2021].

Fukushima Offshore Wind Consortium, n.d. *Fukushima Floating Offshore Wind Farm - Construction of Phase 1*, Tokyo: Fukushima Offshore Wind Consortium.

GICON SOF, n.d. *Media Relations*. [Online] Available at: **http://www.gicon-sof.de/en/media.html** [Accessed 2021 01 06].

GICON, n.d. *Technological Innovations*. [Online] Available at: **http://www.gicon-sof.de/en/technical-solution.html** [Accessed 07 01 2021].

Ideol, 2018. *Floatgen Demonstrator*. [Online] Available at: **https://www.ideol-offshore.com/en/floatgen-demonstrator** [Accessed 2021 01 06].

Intermoor, 2021. *H-Link Mooring Connectors: A More Reliable Fiber-Chain Connection*. [Online] Available at: **https://intermoor.com/press-releases/h-link-mooring-connectors-provide-more-reliable-connection/** [Accessed 08 01 2021].

Intermoor, 2021. *Which Foundation For Your Pipeline Termination?*. [Online] Available at: **https://intermoor.com/press-releases/which-foundation-is-optimal-for-your-pipeline-termination/** [Accessed 07 01 2021].

Nigg Energy Park, 2020. *10 further Moray East offshore jackets arrival at the Port of Nigg*. [Online] Available at: **http://nigg.com/news/10-further-moray-east-offshore-jackets-arrival-at-the-port-of-nigg** [Accessed 26 01 2021].

Nordsee One, n.d. *Inter-Array Cable*. [Online] Available at: **https://www.nordseeone.com/engineering-construction/inter-array-cable.html** [Accessed 08 01 2021].

NREL, 2014. *Offshore Wind Plant Electrical Systems*. s.l., s.n.

Offshore Engineer, 2019. *Interview: Mark Jones, CEO InterMoor*. [Online] Available at: **https://www.oedigital.com/news/466046-interview-mark-jones-ceo-intermoor** [Accessed 07 01 2021].

ORE Catapult, 2019. *Sparta Portfolio Review 2018/19*, Glasgow: ORE Catapult.

PELASTAR, n.d. *PELASTAR*. [Online] Available at: **https://pelastar.com** [Accessed 07 01 2021].

Peterhead Port Authority, 2021. *Renewables*. [Online] Available at: **https://www.peterheadport.co.uk/clients/energy/renewables** [Accessed 26 01 2021].

Philipp R. Thies, L. J. G. H. S., 2011. Assessing mechanical loading regimes and fatigue life of marine power cables in marine energy applications. *Special Issue Proc. of the Institution of Mechanical Engineers, Part O, Journal of Risk and Reliability*, Volume 226, pp. 18-32.

Principle Power, n.d. *Principle Power WindFloat Brochure*. [Online] Available at: **https://www.principlepowerinc.com/fileManager/editor/pdfs/PrinciplePowerWindFloatBrochure.pdf** [Accessed 06 01 2021].

Ramboll, 2020. *COREWIND aims to reduce costs for floating offshore wind turbines.* [Online] Available at: **https://ramboll.com/projects/germany/corewind**

Recharge News, 2020. *Engie/EDPR offshore wind JV to be fully operational within weeks.* [Online] Available at: **https://www.rechargenews.com/wind/engie-edpr-offshore-wind-jv-to-be-fully-operational-within-weeks/2-1-763532** [Accessed 11 01 2021].

Ryota TANINOKI, K. A. T. S. D. A. M. N., 2017. Dynamic Cable System for Floating Offshore Wind Power Generation. *SEI TECHNICAL REVIEW*, Volume 84.

Saipem, n.d. *HYWIND.* [Online] Available at: **https://www.saipem.com/en/projects/hywind** [Accessed 11 01 2021].

Saitec, 2020. *Saitec lands EU funds for 10MW+ floating wind design.* [Online] Available at: **https://saitec-offshore.com/saitec-lands-eu-funds-for-10mw-floating-wind-design/** [Accessed 07 01 2021].

Sant, T. & Cuschieri, K., 2016. Comparing Three Aerodynamic Models for Predicting The Thrust and Power Characteristics of Yawed Floating Wind Turbine Rotors. *Journal of Solar Energy Engineering*, Volume 138.

SBM Offshore, 2016. *SBM Offshore is selected by EDF Energies Nouvelles to provide floating wind systems solution for pilot offshore France.* [Online] Available at: **https://www.sbmoffshore.com/news/sbm-offshore-selected-edf-energies-nouvelles-provide-floating-wind-systems-solution-pilot-offshore-france** [Accessed 07 01 2021].

Scottish Government, 2020. *Sectoral Marine Plan for Offshore Wind Energy*, Edinburgh: Scottish Government.

Statoil, 2016. *Hywind Scotland – status and plans.* Stavanger, s.n.

Statoil, 2017. *Hywind Scotland Pilot Park Project Plan for Construction Activities 2017*, Stavanger: Statoil.

Vryhof, 2020. *STEVMANTA®.* [Online] Available at: **https://vryhof.com/products/anchors/stevmanta** [Accessed 07 01 2021].

Vryhof, 2020. *STEVPRIS® Mk6.* [Online] Available at: **https://vryhof.com/products/anchors/stevpris-mk6/** [Accessed 07 01 2021].

Vryhof, n.d. *Harnessing Offshore Mooring Experience and Anchoring Technology for the Floating Renewable Energy Systems.* [Online] Available at: **https://www.kivi.nl/uploads/media/5ae711f5178c0/SOZ-KIVI%20lecture%20-%20Anchoring%20Technologies%20for%20FOWT%20by%20Vryhof%20Anchors.pdf** [Accessed 16 December 2020].

Whitmarsh, M. et al., 2019. *The UK Offshore Wind Industry: Supply Chain Review*, s.l.: Offshore Wind Industry Council.

Wind Systems, 2019. *Transverse load-out supports floating wind farm.* [Online] Available at: **https://www.windsystemsmag.com/transverse-load-out-supports-floating-wind-farm/** [Accessed 11 01 2021].

FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

Delivered by CATAPULT Offshore Renewable Energy

CONTACT US

ore.catapult.org.uk
info@ore.catapult.org.uk

ENGAGE WITH US

GLASGOW

Inovo
121 George Street
Glasgow
G1 1RD

T +44 (0)333 004 1400

BLYTH

National Renewable Energy Centre Offshore House
Albert Street
Blyth, Northumberland
NE24 1LZ

T +44 (0)1670 359 555

LEVENMOUTH

Fife Renewables Innovation Centre (FRIC)
Ajax Way
Leven
KY8 3RS

T +44 (0)1670 359 555

HULL

O&M Centre of Excellence
Ergo Centre
Bridgehead Business Park
Meadow Road, Hessle
HU13 0GD

ABERDEEN

Subsea UK
30 Abercrombie Court
Prospect Road, Westhill
Aberdeenshire
AB32 6FE

CORNWALL

Hayle Marine Renewables Business Park
North Quay
Hayle, Cornwall
TR27 4DD

PEMBROKESHIRE

MEECE
Pembroke Dock
Pembrokeshire
South West Wales

CHINA

11th Floor, Lan Se Zhi Gu No.5
Ke Ji Avenue, Hit-Tech Zone
Yantai City
Shandong Province
China