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Guide to a Floating Offshore Wind Farm

Published on behalf of the Offshore Renewable Energy Catapult, The Crown Estate and Crown Estate Scotland

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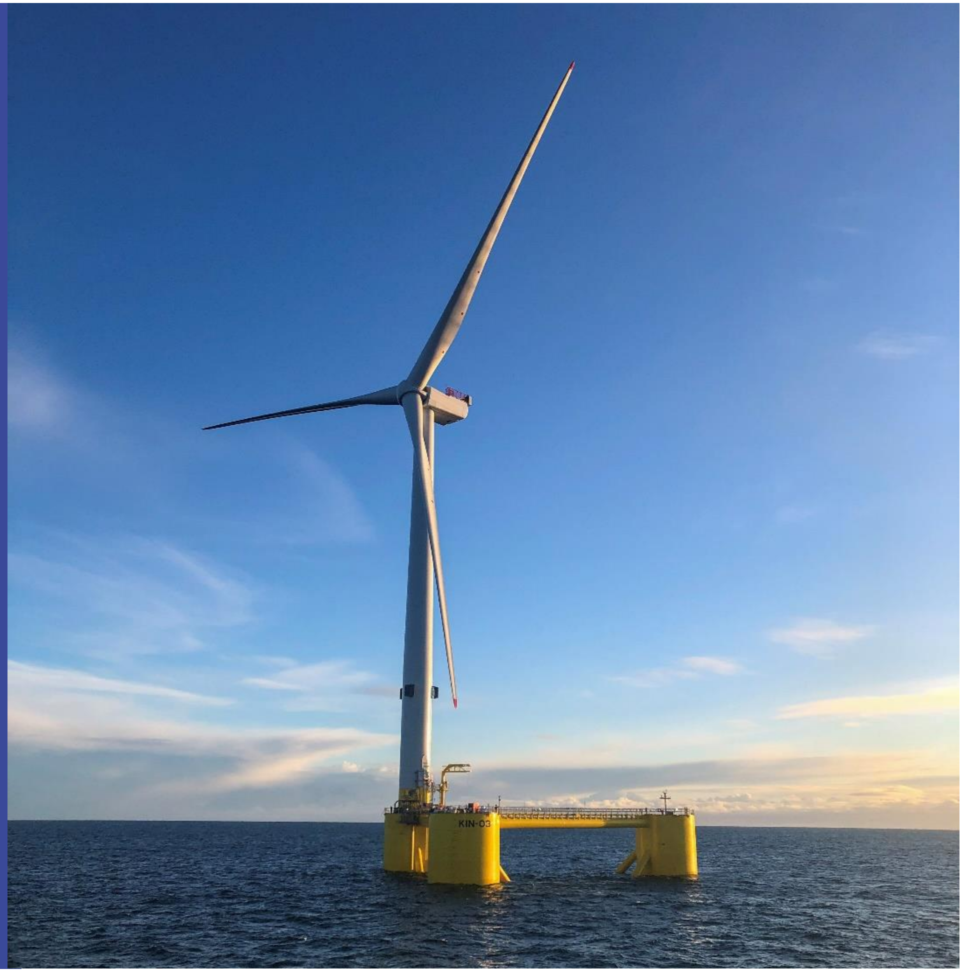

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Front cover image of the Kincardine Offshore Wind Farm project courtesy of Principle Power.

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Offshore Renewable Energy Catapult

The ORE Catapult is playing a leading role in stimulating innovation in offshore wind. It established the Floating Offshore Wind Centre of Excellence, a collaborative programme with industry and academic partners that aims to accelerate the development of floating offshore wind in the UK.

The ORE Catapult and the Floating Offshore Wind Centre of Excellence produce reports on floating offshore wind technology, supply chain and markets.

For more information visit https://ore.catapult.org.uk.

ORE Catapult, together with the Crown Estate, published a related document to this one called "Guide to an Offshore Wind Farm" for fixed offshore projects. For more information visit https://guidetoanoffshorewindfarm.com/.

The Crown Estate

The Crown Estate manages the sea bed around England, Wales and Northern Ireland. It coordinates the offshore wind sea bed leasing rounds in these areas.

For more information visit www.thecrownestate.co.uk.

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- BVGA was formed in 2006 at the start of the offshore wind industry.
- We have a global client base, including customers of all sizes in Europe, North America, South America, Asia and Australia.
- Our highly experienced team has an average of over 10 years' experience in renewable energy.
- Most of our work is advising private clients investing in manufacturing, technology, and renewable energy projects.
- We've also published many landmark reports on the future of the industry, cost of energy and supply chain.

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1. Introduction

1.1 This Guide

The aim of this Guide is to help companies develop a greater understanding of the components and processes involved in the development of floating offshore wind farms in the UK.

The floating offshore wind industry is early in its development, with only a small number of pre-commercial projects installed globally. It is expected to grow significantly, with between 6 and 10 GW of capacity operational by the end of 2030.

There are many challenges still to address, including:

- Development: how to mitigate the impact of floating offshore wind farms on the sea bed and other marine users, as the impact is different from fixed offshore wind farms
- Design: how to accelerate the feedback loop between designing, testing and learning, especially for the floating substructure, mooring system and dynamic cable system, and establish design standards optimised for floating offshore wind
- Manufacture: how to achieve economies of simplification, standardisation and scale, given the current industry maturity
- Offshore operations: how to establish new, efficient and effective ways of working for offshore installation, operations and maintenance (O&M), as there are significant differences from fixed offshore wind farms, and
- Financing: how to give confidence to investors, lenders and insurers regarding performance and level of risk to reduce the financing costs of projects.

The example from fixed offshore wind is that significant progress across similar challenges has been successfully achieved and there is no reason to doubt that the floating offshore wind industry will address its challenges too.

To keep things simple, this Guide uses a single reference design of floating substructure to provide a narrative that can be followed easily. This is a three-column, steel, semi-submersible substructure. It is selected because it has already been demonstrated at two pre-commercial floating offshore wind farms and could be used widely elsewhere. It was not selected to represent the best future solution.

The Guide also uses a set of reference parameters to ground some of the narrative and the cost estimates. These include turbine rating, wind farm rating, final investment decision (FID) date and commercial operations date. These are fully described in Section 1.3.

Where relevant, for each element in the wind farm we cover:

- Function. What the component or service does.
- What it costs. We provide typical prices for a project with parameters described in further sections. We recognise that there can be a range in prices of any element, due to specific timing or local issues, exchange rates, competition and contracting conditions. Prices for large components include delivery to nearest port to supplier and warranty costs. Developer costs (including internal project- and construction management, insurance, typically spent contingency and overheads) are included in the highest-level boxes but are not itemised. The sum of costs in lower-level boxes therefore is often lower than in the highest-level box. Costs, when combined with project life of 25 to 30 years, capacity factor of just over 50% and weighted average cost of capital equate to the bid prices expected by developers of floating projects.

- Who supplies them (examples only). The list of suppliers is indicative rather than exhaustive. We have focused on suppliers with proven capability and generally have not listed suppliers with likely future capability or located distant from the UK (for example in US or China). Nevertheless any omission does not reflect any judgement of a company's capabilities.
- Key facts. Description including dimensions / materials where relevant or what is involved in delivering the service / how it relates to other elements and other relevant information.
- What's in it. We list the sub-components / services described elsewhere in the Guide, or standard components / materials / processes used across a range of industries.

A glossary is provided, recognising that there are many industry-specific or technical terms and abbreviations used in the descriptions.

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1.2 Assumptions used in this Guide

1.2.1 Floating substructure type

This Guide uses a single reference design of floating substructure to provide a narrative that can be followed easily. This is a three-column, steel, semi-submersible substructure.

It is selected because it has already been demonstrated at two pre-commercial floating offshore wind farms and could be used widely elsewhere. It was not selected to represent the best future solution.

1.2.2 Other technology and process assumptions

This Guide also assumes that:

- Each floating substructure uses a three-point mooring with drag embedment anchors
- The offshore substation is supported by a fixed jacket foundation, rather than a floating substructure, and
- Floating offshore wind turbine assembly (the assembly of the turbine onto the floating substructure) takes place at port using an onshore crane or a port-side jack-up vessel.

1.2.3 Site definitions

The site definitions used in this Guide are shown in Table 1. These affect the cost calculations.

Table 1 Site definitions used in this Guide.

Parameter	Data	Unit
Year of FID	2025	
First operation date	2028	
Wind farm rating	450	MW
Turbine rating	15	MW
Water depth at site	100	m
Annual mean wind speed at 100 m height	10	m/s
Distance from offshore substation to export cable landing point on the shore	60	km
Distance from export cable landing point to onshore substation	10	km
Ground conditions: benign, allowing a piled substructure for the substation and drag embedment anchors for the floating offshore wind turbines		

1.3 Floating technology

This section introduces the key floating offshore wind substructure types, other floating offshore wind substructure concepts and materials.

There are about a hundred designs for floating substructures currently being proposed by technology innovators, but only a handful of these have been tested at full scale. These substructure designs have a wide range of different characteristics and performance, and all belong to one of four substructure types that have already been successfully used within the offshore oil and gas industry. These are described below.

1.3.1 Semi-submersible substructures

Overview and description

- Semi-submersible substructures typically consisting of typically three or four buoyant columns or other floating elements at the periphery that are connected using pontoons and/or trusses. They are typically ballasted to provide additional stability.
- At present, only Principle Power's WindFloat has been installed at full scale demonstration.
- Suitable for water depths greater than 40 m.
- Design variables include: the number of columns, placement of tower (eccentric vs central), construction material (steel vs concrete) and ballast system, with some designs opting to use a suspended submerged counterweight to lower the centre of gravity.
- Can be used with a wide range of mooring and anchor configurations.

Figure 1 Example of a semi-submersible floating substructure. ***Photo of the WindFloat Atlantic project courtesy of Principle Power/Ocean Winds.***

Characteristics

- Smaller draft than spar substructures. This enables quayside turbine installation and adjustable ballasting can make the complete structure stable for tow-out and installation.
- Tugs and anchor-handling vessels (AHVs) can be used in broad weather windows, reducing the need for specialist vessels.
- The largest floating substructure type, in terms of length and width.
- Higher mass than tension leg platforms.

- Large sea and land areas are required for the storage and marshalling of substructures during construction.
- Semi-submersibles experience higher wave-induced motions than spars, but lower than barges and experience large heave motions in extreme weather conditions when the wave period is close to their heave natural period.

1.3.2 Barge substructures

Overview and description

- Barge substructures have a single hull that pierces the waterline. They have a large surface area in contact with the water which provides stability, however this can make it more susceptible to wave loading.
- The overall dimensions are less than the equivalent semi-submersible.
- The barge-type floating substructures that have been installed to date are BW Ideol's Damping Pool and Saitec Offshore Technologies' SATH.
- Suitable for water depths greater than 40 m.
- Design variables include: construction material (concrete or steel) and the shape of the single hull which may be square or cylindrical.
- Another key variable between designs is the presence and size of a moonpool to improve the stability of the substructure in rough sea states.
- Can be used with a wide range of mooring and anchor configurations.

Figure 2 Example of a barge floating substructure. ***Image courtesy of BW Ideol. All rights reserved.***

Characteristics

- The turbine can be erected onto the barge substructure in a sheltered harbour then towed to the installation site because the combined structure is stable in transport.
- Reduced transport and installation cost associated with building floating projects using barge substructures compared to spars, which can only use specialist marshalling ports because of their depth, or tension leg platforms (TLPs), which need specialist solutions for transport and installation because they have low stability until installed.

- Barges may experience large heave motions in extreme weather conditions when the wave period is close to its heave natural period. This may require turbines installed on barge-type substructures to be engineered for larger tower motions than for other substructure types.

1.3.3 Spar substructures

Overview and description

- Spar substructures use ballast-stabilised designs. They consist of a tall cylinder housing dense ballast in its lower part to lower the centre of gravity below the centre of buoyancy, creating a self-righting motion.
- Spar substructures have a large draft.
- This substructure type has been used by Equinor at its first three projects in the in the North Sea, which have used concrete and steel-based designs.
- Suitable for water depths above 100 m.
- Design variables include: construction material, ballast material, and the size of the cylinder.
- Can be used with a wide range of mooring and anchor configurations.

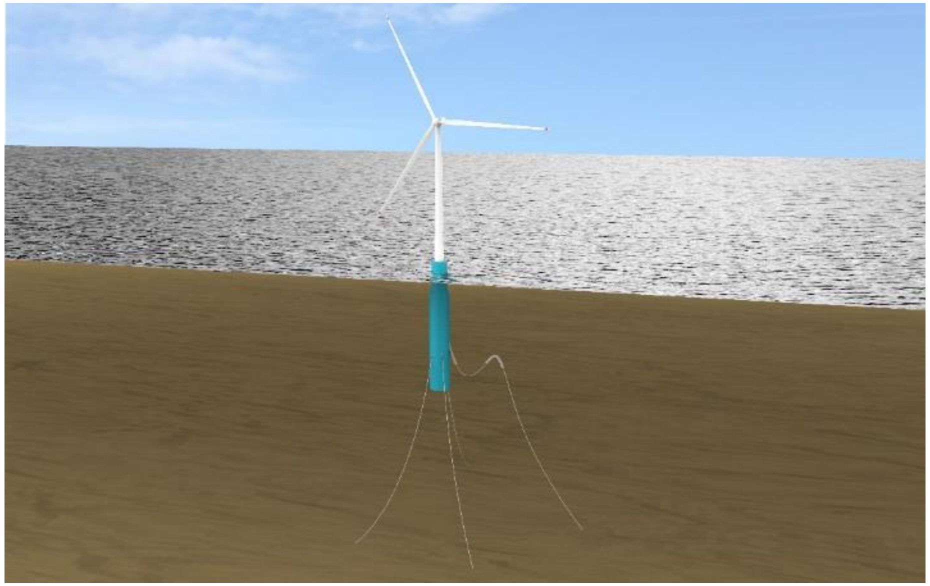

Figure 3 Example of a spar floating substructure. *Image courtesy of ORE Catapult. All rights reserved.*

Characteristics

- Its large draft and small waterplane area mean it is less affected by wind, wave and current compared to other designs.
- The large draft means that assembling turbines onto substructures from the quayside requires deep-water locations, which may not be available in some areas. This may also be done using floating installation vessels in sheltered deep-water areas, such as the Norwegian fjords, but this adds cost.
- The large draft also limits site locations to allow tow-out for installation and tow-back for major-component replacement.

- It has the highest tilt during normal operations of all technology types, and active ballasting is not an option to address this.

1.3.4 Tension leg platforms

Overview and description

- TLPs achieve stability through the mooring system. They typically use mooring lines that connect to anchors either vertically or predominantly vertically. The upwards buoyancy force acting on the hull needs to be sufficient so that the tendons are continuously under tension under all operating loads.
- TLPs are well established in the oil and gas industry but have not been used with wind turbines, up to now, on any commercial-scale demonstration projects.
- A star-pontoon arrangement is expected to be used for floating offshore wind turbine applications with minimal structure piercing the waterline and minimal steel mass.
- The first full-scale TLP demonstrator in offshore wind is expected to be SBM Offshore's design at Provence Grand Large, France, in 2023.
- Suitable for water depths above 80 m.
- Design variables include: construction material, the shape of the hull and whether there is any active adjustment of the tendon load.
- The high loading in the mooring system, and their vertical, or near vertical, configuration, requires an anchor type that can withstand a strong vertical pull, such as a driven pile or a suction anchor.

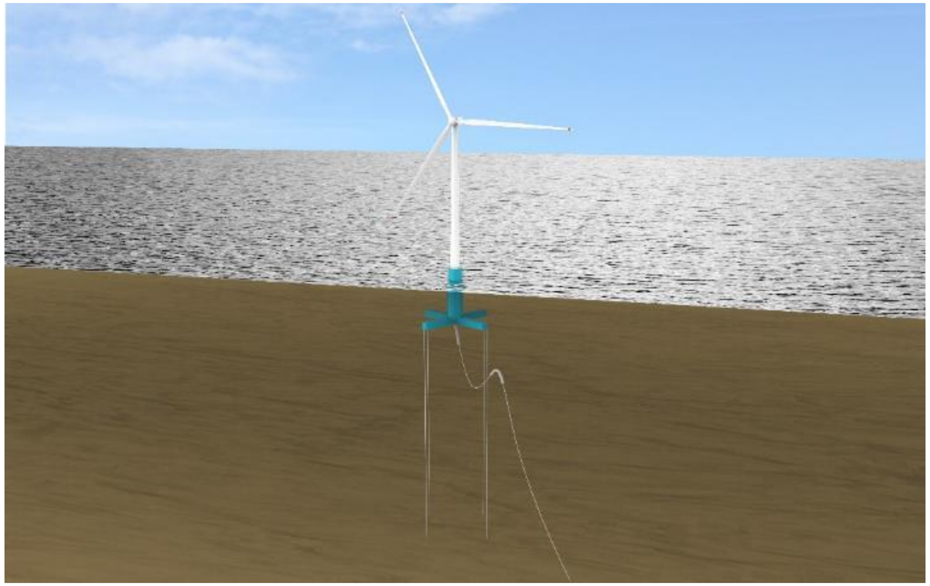

Figure 4 Example of a tension leg platform floating substructure. ***Image courtesy of ORE Catapult. All rights reserved.***

Characteristics

- Installation is complex as the hull is less stable than other technology types. This means that final assembly of the turbine onto a TLP in port followed by tow out to site is not possible.
- It is expected that either turbines will be assembled onto installed TLPs at site, requiring a weather sensitive floating-to-floating lift, or pre-assembled on a vessel capable of installing the turbine and TLP together. This also makes tow-to shore options for maintenance harder than for other floating foundation types.

- The mooring system and anchors are expected to be more expensive than for other technology types as they are subjected to higher loads and they require sufficient redundancy to counter the consequence of failure.
- It has the lowest structural mass of all floating substructure types once installed, although this has to be set against the higher costs of transport and installation, and the mooring system and anchors.
- The lowest substructure motions of all floating substructure types other than spars once installed. This reduces the structural loadings on the turbine and array cables compared to other types.
- As the mooring system is critical to stability there could be reluctance to use it in areas prone to seismic activity.

1.3.5 Other floating offshore substructure concepts

The other floating offshore wind substructure concepts included here are variants of the four substructure types previously described, but sufficiently novel to describe further. Many offer the potential for significant mass reduction but often increase the complexity of design. Lessons from the oil and gas industry has shown the benefits of simplicity over complexity. It is important, however, that the industry properly examines other concepts.

The non-exhaustive list of example concepts included here are intended to show the spread of potentially disruptive solutions.

- Counterweight concepts. One example is Saipem's Hexafloat, see Figure 5. These combine the benefits of a semi-submersible (shallow depth for transport) and a spar (stability from mass at depth). A challenge is the complexity of mechanisms to lower and raise the counterweight.
- Pivoting about a single point, thus removing the need for a turbine yaw system and ability of the support structure to withstand loads from all directions. Examples include X1 WIND's PivotBuoy, Aerodyn's Nezzy2 and Saitec's SATH, see Figure 6. These use turret mooring/single point moorings, which is a proven technology for floating production storage and offloading solutions (FPSOs) in oil and gas. A challenge is how the floating offshore wind turbine behaves when strong waves or tide are not aligned with the wind direction.
- Downwind rotor. Examples include X1 WIND's PivotBuoy and Aerodyn's Nezzy2, see Figure 6 and Figure 7. These are typically enabled by a pivoting substructure and allow unconventional tower concepts such as tower braces, guyed towers or inclined towers. A challenge is that the established wind turbine manufacturers are focused on turbine concepts relying on a yaw system that can be used onshore and on fixed offshore substructures.
- Multiple rotors. Examples include Hexicon, and Aerodyn's Nezzy2, see Figure 7. These are typically enabled by a pivoting substructure and have the potential to reduce the cost of the floating substructure and array connection per MW, having double the installed capacity on a single floating substructure. A challenge is the impact of one turbine shutting down on the other(s).
- Vertical axis floating wind turbines. Examples include SeaTwirl's S1 and S2, see Figure 8. A challenge is that vertical axis wind turbines on land have had higher levelised cost of energy (LCOE) than horizontal axis turbines due, in large part, to their rotors having lower coefficients of performance.
- Combined wind and wave energy devices: examples include Floating Power Plant (FPP), see Figure 9.

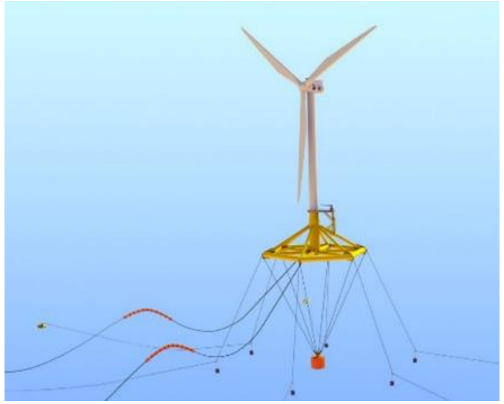

Figure 5 Floating substructures with counterweights. ***Saipem's Hexafloat (image courtesy of Saipem, all rights reserved).***

Figure 6 Floating substructures which pivot about a single point. ***From left to right: X1 WIND's PivotBuoy (image courtesy of X1 WIND, all rights reserved) and Saitec's SATH (image courtesy of Saitec, all rights reserved).***

Figure 7 Floating substructures with multiple rotors. ***From left to right: Hexicon's TwinWind (image courtesy of Hexicon, all rights reserved) and Aerodyn's Nezzy2 (image courtesy of Aerodyn, all rights reserved).***

Figure 8 Vertical axis floating substructure. ***SeaTwirl's S2 (image courtesy of SeaTwirl, all rights reserved).***

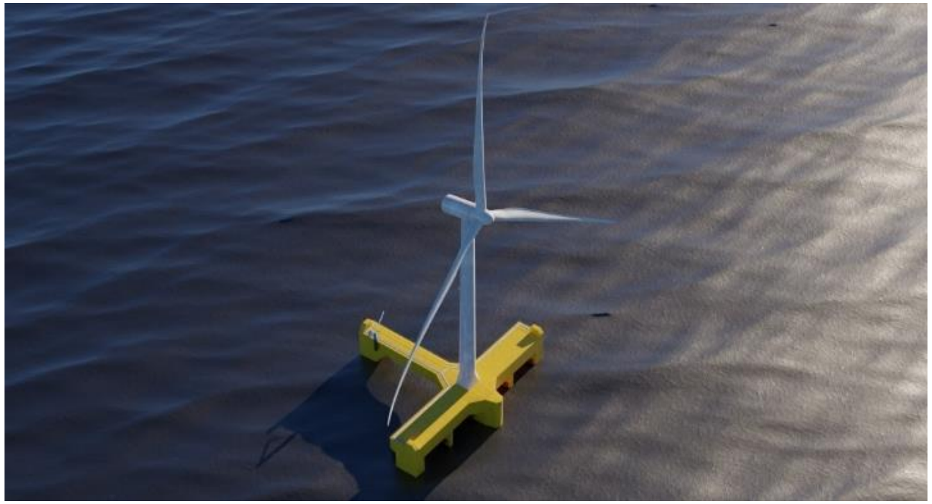

Figure 9 Combined wind and wave device. *Floating Power Plant's substructure (image courtesy of Floating Power Plant, all rights reserved).*

1.3.6 Concrete versus steel as the primary material

Floating substructure types can be designed using either steel, concrete or a hybrid of the two. The decision on what materials to use may be taken on a case-by-case basis considering a wide range of factors. For example, Equinor used steel spar substructures at its 30 MW Hywind Demo project in 2017 and concrete spar substructures at its 88 MW Hywind Tampen project.

There are four main factors which influence a developer's choice of materials:

Cost

- A developer's decision to use steel concrete or hybrid substructures will involve careful consideration of the costs across all project phases.
- Steel is expected to be less expensive per tonne than concrete but steel reinforcing bar is cheaper than steel plate.
- Steel plate prices have been more volatile, with swings up to 50% recorded within a year. Concrete prices tend to be more stable. Reinforced concrete structures still use large amounts of steel, especially for reinforcement, but the overall volume is several times less than where steel is the primary material.

Supply chain

- Where there is no existing steel fabrication supply chain locally, concrete fabrication may be more straightforward to establish as it requires less investment in new facilities.
- The localisation of concrete fabrication provides a larger number of jobs compared to a steel fabrication yard. The jobs associated with steel and cement manufacture must also be considered.
- Concrete substructures are heavier than steel so require more effort to lift or tow, and greater channel depth, if transporting them is needed.

Environmental impact

- Environmental considerations are important for developers and may be included as decision criteria in competitive offtake auctions. The carbon footprint depends on how the steel and cement are made, the operational lifetime and any recycling or re-use at end of life.
- Steel is frequently recycled. It is expected that concrete would be ground up. Lifecycle analysis is a useful tool for this sort of analysis.

Site conditions

- Metocean conditions may influence the selection of material due to the performance of different materials through time. For example, concrete substructures are likely to be more vulnerable to freeze-thaw damage while steel foundations are likely to be more vulnerable to corrosion.

P Development and project management

Function

Development and project management covers the activities up to the point of final investment decision (FID) and managing the construction of the project through to commercial operations date (COD). This includes activities required to secure planning consents, such as the environmental impact assessment (EIA), activities required to define the design and engineering aspects, and all aspects of project management.

What it costs

About £66 million for a 450 MW floating offshore wind farm. This does not include any site leasing costs incurred by the project developer. It does include development expenditure incurred by lost projects (not itemised in sections below) to enable a realistic industry LCOE.

Who supplies this

The development and consenting stage is managed by the floating offshore wind farm developer. The main floating offshore wind developers include Bluefloat, BP, Copenhagen Infrastructure Partners, Corio, EDF, EnBW, Equinor, ESB, Falck, Iberdrola, Northland, Ocean Winds, Ørsted, RWE, Shell, Simply Blue, SSE and TotalEnergies.

Key facts

There are no major differences in the development and project management processes between floating offshore wind farms and fixed offshore wind farms.

The environmental impacts can be different in some areas, for example mooring lines could have a larger impact on fishing activities.

Sea bed leasing for existing floating offshore wind farms has been managed by The Crown Estate and Crown Estate Scotland through several leasing rounds that began in 2000.

The Crown Estate manages the sea bed in the territorial waters of England, Northern Ireland, and Wales and adjacent areas of the United Kingdom EEZ. Crown Estate Scotland manages the sea bed in Scottish territorial waters and adjacent areas of the United Kingdom Exclusive Economic Zone (EEZ).

Before the consenting process can begin, the developer must secure a sea bed lease from The Crown Estate or Crown Estate Scotland. These are granted through periodic leasing rounds.

In England and Wales, offshore wind projects of more than 100 MW installed capacity are defined as nationally significant infrastructure projects (NSIPs) and are examined by the Planning Inspectorate.

The Secretary of State for the Department for Business, Energy, and Industrial Strategy (BEIS) grants or refuses consent based on a recommendation made by the Planning Inspectorate.

In England, a Development Consent Order is granted under the Planning Act 2008 (as amended) which incorporates a number of consents, including a marine licence and onshore consents. In Wales, the marine licence is determined by Natural Resources Wales.

In Scotland, Marine Scotland examines applications for the offshore works and Scottish Ministers grant or refuse consent under the Marine (Scotland) Act of 2010 (up to 12 nm from shore) and the Marine and Coastal Access Act 2009 for projects 12 to 200 nm from shore. A streamlined process incorporates consent under Section 36 of the Electricity Act 1989 in parallel.

In Northern Ireland, the Marine Strategy and Licensing team within the Department of Agriculture, Environment and Rural Affairs (DAERA) manages the consent application and decision-making process for offshore wind projects.

Other important aspects of the development process include securing land permissions for onshore substations and cable routes and engaging with the supply chain.

Onshore consent including the transmission cable landfall and associated onshore grid connection infrastructure is awarded by the relevant local planning authority, except where a project is handled under an NSIP in England and Wales, in which case the onshore consents are considered within the NSIP process.

Developers typically build internal teams of up to 50 staff during the development phase, which contract specialist packages of work to environmental and engineering consultancies and data acquisition and analysis companies.

The development process from first consideration of a site to FID typically takes between four and seven years in the UK. The offshore wind industry, and in particular some of the organisations which regulate it in Europe, are looking at how it can be accelerated.

What's in it

- P.1 Development and consenting services
- P.2 Environmental surveys
- P.3 Resource and metocean assessment
- P.4 Geological and hydrographical surveys
- P.5 Engineering and consultancy
- P.6 Project management

P.1 Development and consenting services

Function

Development and consenting covers the work needed to secure consent and manage the development process through to FID.

What it costs

About £31 million for a 450 MW floating offshore wind farm. This includes environmental impact assessments plus staff costs and other subcontractor work (neither of these itemised in sections below).

Who supplies this

Development services are typically led by the developer's special purpose vehicle (SPV), which manages the development process and subcontracts work to a range of specialist consultancies. The SPV is a legal entity, which invests in and owns the floating offshore wind farm project.

Key facts

Developers typically set up a SPV for a wind farm. Should the project advance to construction, the SPV will continue to operate for the duration of the offshore wind farm's life.

In instances where the SPV is a joint venture between two or more developers, it is likely that the development team will be based in stand-alone offices to manage confidentiality.

The SPV provides a structure to enable external investment, although this investment is most likely to take place at FID or post construction.

In the UK, the SPV manages the design of the floating offshore wind farm and secures consent for the floating offshore wind farm and transmission assets.

An early formal step in the consenting process is the production of a scoping report, the purpose of which is to scope the level of impact on various receptors in order to properly define the required assessment process and methodologies, and to ensure the EIA focuses on those impacts that may lead to substantial effects. It also provides an early opinion from the planning authorities to help shape and focus the development activity.

Developers aim to secure planning consent while retaining as much design flexibility as they can. A particular risk for developers is specifying a specific foundation solution or a maximum turbine size, which may prove to be restrictive at the point of procurement and require the developer to request variations to the consents they have already been granted.

Design flexibilities around the floating offshore wind sector makes the environmental impacts less certain and difficult to analyse. The range of options included in the proposed design is known as the design envelope, which includes a clear upper and lower bound on the scale of the project, for example in terms of turbine tip height.

Developers need to undertake an EIA, which describes the potential impacts with regards to a wide range of environmental factors.

The environmental statement is based on a number of detailed analyses. Most offshore wind developers have a predominantly in-house development management capability, with specialist work being outsourced. Specialist suppliers will often second employees into the developer's team for the duration of the development phase.

Throughout the development process, developers are obliged to seek the views of a number of statutory consultees. These include a wide range of government appointed consultees and authorities, affected local authorities and those that have an interest in the land affected. Non-statutory consultees with specific interests in the development are also likely to be consulted, such as the RSPB

Developers also seek the views of local communities as part of this process and hold a series of public information and consultation events. Floating offshore wind farms have a greater sea bed footprint than fixed offshore wind farms, requiring multiple anchors for each turbine. They also have mooring lines and dynamic cables in the water column which fixed offshore wind farms do not. These factors require engagement and consultation with local communities and fisheries.

Supporting the work will be a range of specialist consultants, covering engineering design, legal issues, land use, environmental and stakeholder relations.

What's in it

- P.1.1 Environmental impact assessments

P.1.1 Environmental impact assessments

Function

An EIA assesses the potential impact of the proposed development on the physical, biological, and human environment during the construction, operation and decommissioning of the floating offshore wind farm.

What it costs

About £4.6 million for a 450 MW floating offshore wind farm.

Who supplies this

Atkins, ERM, GoBe, Mott MacDonald, Natural Power, Royal HaskoningDHV, RPS and Xodus.

Key facts

The most recent EIA regulations specify that the assessment must consider impacts on human health, climate change and biodiversity. To determine the impacts, a full suite of environmental surveys is undertaken.

After assessing the potential impacts, mitigation measures are defined and applied in order to determine the residual effects associated with the development. A core part of the EIA is the Cumulative Impact Assessment (CIA) where the development's impacts combined with those impacts from other foreseeable projects are assessed. The EIA is used to inform the Environmental Statement (ES) (or EIA Report), which forms the core evidence that is submitted to support a consent application.

Consultation with statutory consultees, special interest groups and the local community is performed throughout the EIA process and allows the consenting authority, as well as other stakeholders and the public, to voice their opinions and concerns.

The EIA process can take up to three years to complete, with the main driver being the length of time it takes to complete the required environmental surveys.

Under the Habitats Directive and the Conservation of Habitats and Species Regulations 2010 (as amended), developers should consider the potential effects on protected habitats. If the development is likely to affect a designated European site, the developer must provide a report with the application showing the designated European site that may be affected together with sufficient information to enable the decision maker to make an assessment, if required. In the UK, a Habitat Regulations Appraisal (HRA) is performed as an integral part of an EIA to ensure that a project conforms to The Conservation of Habitats and Species Regulations (2010).

What's in it

- Assessment
- Environmental Statement
- Habitat regulations assessment
- Mitigation
- Residual impacts
- Scoping
- Site-specific impacts

P.2 Environmental surveys

Function

A full suite of environmental surveys of the floating offshore wind farm location and its surroundings is undertaken to determine the environmental impacts. These surveys establish the baseline for the assessment and allow impact modelling to be undertaken.

What it costs

About £4 million for a 450 MW floating offshore wind farm.

Who supplies this

APEM, ERM, Fugro, Natural Power, RPS, RSK and SLR.

Key facts

Environmental surveys are one of the first tasks to be undertaken at a potential offshore wind farm site and it can take two years or more before sufficient data is collected in order to apply for consent. Floating offshore wind farms have a greater emphasis on certain environmental surveys compared to fixed offshore wind farms. This is to understand and mitigate environmental impacts, if any, because of the larger sea bed usage.

The surveys include bird, fish, marine mammal, and habitat surveys as well as marine navigation studies, socio-economic surveys, commercial fishing, archaeology, noise analysis, landscape and visual assessment and aviation impact assessments.

Companies and developers recognise more detailed surveying can reduce costly consenting delays and post-construction environmental monitoring requirements.

Some surveys need to establish regional behaviours of wildlife, for example bird feeding and breeding patterns, and in these cases, data may need to be collected for several years. For highly mobile wildlife populations such as birds or sea mammals, it may be difficult to establish whether the predicted impacts during construction will be enduring.

Vessels and aircraft are used to collect the survey data. Surveys look at the distribution, density, diversity, and number of different species.

A challenge in the assessments is trying to understand the cumulative impacts of several wind farms, particularly when these are the subject of separate EIAs and consenting processes.

Some environmental surveys are undertaken by companies that also offer geological or hydrological surveys; in which case the work can be conducted from the same vessels in a single campaign.

Environmental surveys are typically undertaken by companies from the home market, partly because there is sufficient local resource and partly because some of the wildlife impacts are site specific and require detailed local knowledge and expertise.

Under the Offshore Wind Evidence and Change programme, The Crown Estate along with Natural England, Scottish Government and the Royal Society for the Protection of Birds has launched three new projects to protect and enhance marine biodiversity while encouraging offshore wind deployment. The projects are POSEIDON (Planning Offshore Wind Strategic Environmental Impact Decisions), PrePARED (Predators and Prey Around Renewable Energy Developments) and Remote Tracking of Seabirds at Sea.

What's in it

- P.2.1 Offshore species and habitat surveys

P.2.1 Offshore species and habitat surveys

Function

Species and habitat surveys are conducted to understand the potential impacts of a floating offshore wind farm on habitats and species and to inform impact analysis and reporting.

What it costs

About £3.1 million for a 450 MW floating offshore wind farm.

Who supplies this

ABPmer, APEM, Fugro, Gardline, HiDef Surveying, Natural Power, Precision Marine and RPS.

Key facts

Species and habitat surveys includes benthic, fish and shellfish, ornithological and marine mammal surveys. Benthic species live on the sea bed and in sediment. The survey data is used to define areas of similar environmental conditions on the sea bed and to inform habitat and species impact studies. More extensive benthic surveys are required for floating offshore wind farms compared to fixed to understand the potential sea bed impacts of the multiple anchoring points required. We expect these surveys to be conducted for all anchor placements initially to produce the most effective broad-scale categorisation of the overall region, as well as attempting to investigate smaller scale features such as reefs. As floating offshore wind technology matures, this may involve sampling of a regular grid. Methods include grab sampling, epibenthic beam trawling and drop-down video (DDV).

Fish and shellfish surveys establish what species are present in the water column within the proposed floating offshore wind farm site and surrounding areas. Beam trawls or otter trawls (dragging a net along the sea bed) are used to sample the species present in the area. Other fishing methods such as lobster pots or gill nets can also be used in areas where trawling cannot take place. Plankton nets can be used for fish egg and arval studies. Surveys are generally undertaken to characterise the species present in the area of the floating offshore wind farm, but also to address specific questions such as whether fish are spawning in the area, should this be an issue for EIA. Surveys can often be done using local fishing vessels, providing they reach minimum safety standards. This approach offers the potential for good engagement with the local fishing community.

Ornithological surveys establish the presence and behaviour of birds within the floating offshore wind farm boundary and surrounding areas. The data from these bird surveys is used to establish the risks to birds that a floating offshore wind farm may pose. Offshore ornithological studies are normally one of the first tasks to be undertaken at a potential floating offshore wind farm site because at least two years of data are needed to establish baseline conditions. This is due to the high level of spatial and temporal variation in bird abundance and distribution throughout the annual cycle. Boat-based and digital aerial surveys are typically used to establish population estimates and to gather behavioural data including species' flight heights (a key variable used to assess potential collision). Other methods such as GPS tracking, lidar, radar and coastal vantage point surveys can also be used.

Marine mammal surveys establish the diversity, abundance, distribution, and behaviour of cetaceans (including porpoises, dolphins and whales) and seals within the floating offshore wind farm boundary and surrounding areas. Surveys are typically undertaken monthly for at least two years to establish how these variables change across seasons and between years. Marine mammals are surveyed to determine how they make use of the proposed area and therefore the different effects that a floating offshore wind farm may have. These could include potential disturbance and displacement, physical and auditory injury during pile driving, and both direct and indirect habitat loss (for example through effects on prey species). Detailed modelling is conducted to understand the interaction between marine mammals and floating offshore wind components like cables and mooring lines. The methods used depend on the species and site. Traditional visual surveys using boat and aerial platforms are being supplemented or replaced by new, more accurate technologies such as static and towed acoustic monitoring, tagging of individuals with satellite transmitters and remotely controlled video monitoring.

What's in it

- Benthic environmental surveys
- Fish and shellfish surveys
- Ornithological environmental surveys
- Sea mammal environmental surveys
- P.2.1.1 Offshore ornithological and mammal surveying vessels and aircraft

P.2.1.1 Offshore ornithological and mammal surveying vessels and aircraft

Function

Bird and marine mammal survey vessels and aircraft provide a platform for surveying to take place.

Who supplies this

Vessels: Enviro-serve, Fugro and Gardline.

Aircraft: APEM, Green Rebel and HiDef Surveying.

Key facts

Traditional visual methods for surveying marine mammals are often undertaken concurrently with offshore ornithology surveys, offering a cost saving. For the floating offshore wind sector, unfavourable weather and sea conditions have to be considered in the planning of surveys to ensure that the data collected is robust.

Multiple crews are used, including experienced and qualified surveyors, who rotate in shifts in order to avoid fatigue and maintain visual acuity. Traditional visual boat-based surveys can be supplemented with a towed hydrophone and acoustic pods deployed on the sea bed to undertake passive acoustic monitoring of marine mammals.

Whilst traditional visual aerial surveys can be used to record marine mammals, these are not suitable to record marine birds as they fly at relatively low altitudes and can cause disturbance (and therefore the data collected are not representative of baseline conditions). Instead, digital aerial survey aircraft can be used which fly at higher altitudes, recording both birds and marine mammals.

These survey aircraft have a range of remote sensing instruments on board such as high-resolution digital cameras, lidar, video imaging and imaging spectrometers. Twin-engine planes, with long-range fuel tanks and autopilot capabilities allow for extensive surveying offshore without the need for on-board surveyors.

There is great potential for the increased use of autonomous vessels with remote sensing instruments and artificial intelligence to analyse data, to reduce cost and carry out more extensive offshore surveys.

What's in it

- Aircraft
- Provision of suitably experienced and qualified crew
- Survey vessels

P.2.2 Onshore environmental surveys

Function

Onshore environmental surveys consider the potential ecological impact that cable laying, onshore substations and new port facilities may have on the onshore environment.

What it costs

About £520,000 for a 450 MW floating offshore wind farm.

Who supplies this

Andrew McCarthy Associates, APEM, BCM Environs, ESS Ecology, Natural Power, RSK and Thomson Ecology.

Key facts

Wildlife surveys are often undertaken by ecological companies who have specialised capabilities for particular species.

Studies tend to look at the distribution, density, and number of different species.

Wildlife ranging from badgers to small reptiles are considered, depending on the nature of the proposed site.

Fragile coastal ecosystems are a prime area of focus.

What's in it

- Data analysis
- Surveying
- Reporting

P.2.3 Human impact studies

Function

Human impact studies assess the impact that a proposed floating offshore wind farm may have on the community living in and around the coastal area.

What it costs

About £520,000 for a 450 MW floating offshore wind farm.

Who supplies this

ERM, Hayes Mackenzie, Hoare Lea, LUC, Royal HaskoningDHV, RPS and SLR.

Key facts

Visual assessments comprise photomontages from specific viewpoints of what the proposed wind farm will look like. Noise assessments assess that potential noise impacts and determine whether the impact of the proposed floating offshore wind farm is within the guidance of relevant noise standards. Other areas studied include fisheries and archaeology.

The socioeconomic study assesses the impacts of a floating offshore wind farm or coastal infrastructure, for example a port, on changes in employment, transportation or recreation, or changes in the aesthetic value of a landscape. It estimates the impacts on the local society, not only of these socio-economic changes, but also of the composite of biological, geological, and physical effects caused by the proposed change on the local area.

Socio-economic studies include a mix of objective and subjective data. Objective data can include statistics on age, income distribution, ethnicity, mortality, housing type and occupancy, and education. Subjective data can be derived from surveys and observations. These are used to provide systematic estimates of the ways in which various groups perceive their socio-economic environment and thus the impact of the proposed change. Studies consider the onshore cable route and substation.

What's in it

- Consultation
- Surveys

P.3 Resource and metocean assessment

Function

Resource and metocean assessments provide atmospheric and oceanographic datasets to inform the engineering design of a floating offshore wind farm, the potential future energy production, and to fully describe the likely installation and operating conditions at the proposed floating offshore wind farm location.

Figure 10 Example of a floating lidar used to capture atmospheric data. ***Image courtesy of EOLOS. All rights reserved.***

What it costs

About £3 million for a 450 MW floating offshore wind farm.

Who supplies this

Floating lidars: AXYS Technologies, EOLOS, EOLFI, IDS Monitoring, Fraunhofer IWES, Fugro, RPS and ZX Lidars.

Lidar units: Leosphere and ZX Lidars.

Metocean campaigns and buoys: AXYS Technologies, Fugro and Partrac.

Reference data provision: The Met Office, StormGeo and Vortex.

Resource campaign management and design: AXYS Technologies, DNV, Fugro, K2 Management, Natural Power, Oldbaum and ZX Measurement.

Key facts

Measurement systems are installed at the project location to collect wind and other relevant meteorological data. Meteorological sensors measure wind speed (with instruments at a number of heights or measuring over a range of heights with one sensor), wind direction, temperature, pressure, humidity, solar radiation and visibility. Measuring wind speeds at different heights provides critical information about the wind speed profile at the site, aiding decisions about the turbine and floating substructure design. Wind speed data is required to at least the proposed hub-height of the wind turbines, which is 130 m or more above sea level for a 15 MW turbine. Metocean buoys are installed in and around the floating offshore wind farm site to collect metocean data. Metocean sensors include wave, sea level and current sensors (for example acoustic Doppler current profiler) which are sometimes sea bed positioned. These record the full wave data spectrum including velocity, direction, and period. Multiple sensors are used to provide spatial coverage and redundancy. This information is crucial in establishing whole system dynamics including substructure design types, turbine ratings, vessel types and operations and maintenance (O&M) strategies.

In comparison to fixed offshore wind farms, floating offshore wind farms require the same assessments of wind data but require more metocean data for modelling whole system dynamics.

Long-term reference datasets are required to describe the climatology of the proposed site over a longer period typically more than 15 years. Data is usually collected for a period of at least one year to reflect seasonal variation in wind resource and metocean conditions.

These combined data sets are used in the floating offshore wind farm system design process, the turbine selection process and to predict the annual energy production (AEP) of the floating offshore wind farm. Metocean data is also used to inform the vessel selection and operational strategies for the site and is made available to vessel operators and marine planners during the construction and operational phases.

A key interface exists in determining the long-term site conditions between wind resource and metocean disciplines. The output from this interface is the extreme wind and wave climate for the proposed site.

Fixed offshore wind farms have traditionally used hub-height wind masts which are fixed to the sea bed requiring a subsea structure, but the trend is towards the use of floating lidars. Floating offshore wind farms are likely to use floating lidars instead of fixed met masts.

Lidars are a type of remote sensing anemometry device which uses lasers to measure wind speed and direction at up to 300 m above sea level. Floating lidars are moored buoys on which lidars are mounted. This allows the lidars to be deployed and change location as per demand.

When using lidar as the primary measurement instrument, supplementary modelling may be used to inform site conditions such as turbulence and horizontal wind gradients.

Wind and metocean measurement systems require power supply to run sensors, data storage and telemetry. For low power systems this is often achieved with solar PV panels, small wind turbines and battery storage. Larger systems use diesel generators or hydrogen fuel cells.

Current state of the art campaigns integrates measurement and modelling techniques across both oceanographic and wind resource disciplines. The study can be further broadened to look at further issues such as turbulence, atmospheric stability conditions and the influence of neighbouring floating offshore wind farms on the proposed site wind conditions.

Resource and metocean systems require maintenance, including inspection, cleaning, and refuelling (where diesel generators or hydrogen fuel cells or similar are used). Maintenance visits are typically carried out two to four times per year. Systems are designed to operate autonomously, with onboard power, data, and communications systems.

Sensors provide data on meteorological and oceanographic conditions at the site of interest. Data loggers provide data storage, processing, and remote communications capability.

What’s in it

- Anemometers
- Buoys
- Data loggers
- Lidar systems
- Maintenance
- Meteorological sensors
- Metocean sensors
- Wave measurement sensors

BVGAssociates

P.4 Geological and hydrographical surveys

Function

Sea bed surveys analyse the sea bed environment of the proposed floating offshore wind farm site and export cable route to assess its geological condition and engineering characteristics. The data collected is utilised in a wide range of engineering and environmental studies through the design and development phase.

What it costs

About £4 million for a 450 MW floating offshore wind farm.

Who supplies this

CMS Geoscience, EGS, Fugro, Gardline, Horizon Geosciences and MMT.

Key facts

Sea bed surveys consist of two main parts: non-invasive geophysical surveys of sea bed features and bathymetry, and invasive geotechnical surveys of the sea bed characteristics.

Sea bed surveys are an important component of the development process and aid several processes, such as optimising the mooring system designs and floating offshore wind farm layout, as well as minimising risk during installation activities.

Environmental and sea bed surveys and data collection (geotechnical and geophysical) can start five years or more before the planned operation of the floating offshore wind farm.

Offshore wind development typically requires more data collection over larger areas, but the technical approaches are like other sectors, such as oil and gas.

The move to auction-based systems, such as Contract for Differences (CfD) in the UK, has placed a greater emphasis on geological and hydrographical surveys as developers require greater cost (and hence design) certainty earlier in the development process.

What's in it

- P.4.1 Geophysical surveys
- P.4.2 Geotechnical surveys
- P.4.3 Hydrographic surveys

P.4.1 Geophysical surveys

Function

Geophysical surveys establish sea floor bathymetry, sea bed features, water depth and soil stratigraphy, as well as identifying hazardous areas on the seafloor and human-made risks such as unexploded ordnance (UXO).

What it costs

About £1.1 million for a 450 MW floating offshore wind farm.

Who supplies this

Acteon, Argeo, Fugro, Gardline, G-tec, Horizon Geosciences, Magseis Fairfield, MMT, PanGeo Subsea and TGS.

Key facts

Geophysical surveys are non-intrusive and include remote sensing techniques such as seismic methods, echo sounding and magnetometry.

The techniques used consist of bathymetry (water depth) mapping with conventional single or multibeam echo soundings or swathe bathymetry, sea floor mapping with side scan sonar, magnetometer for UXO, acoustic seismic profiling methods and high-resolution digital surveys.

Surveys run along transects across zones within the proposed floating offshore wind farm site and cable routes.

Information from geophysical surveys is used to aid the design and implementation of the benthic and geotechnical surveys, so they are often undertaken near the beginning of the development process.

Data from geophysical surveys are also used to produce charts, models, and maps for GIS systems, which are then used for site layout design.

Geophysical surveys can be used to identify UXO on or below the sea bed.

Geophysical surveys may also consider marine archaeology that may be present in the floating offshore wind farm site. This is typically dealt with by specialist archaeological survey companies and is offered as a service in conjunction with geophysical surveys.

What's in it

- P.4.1.1 Geophysical survey vessels

P.4.1.1 Geophysical survey vessels

Function

Specialist vessels are used to carry out geophysical surveys of the sea bed.

Figure 11 A specialist geophysical survey vessel. *Image courtesy of Fugro. All rights reserved.*

Who supplies this

Fugro, Gardline, Horizon Geosciences and MMT.

Key facts

Geophysical vessels are typically about 30 to 70 m in length. The vessels must provide a stable platform even in unfavourable sea and weather conditions.

Multiple crews, including highly specialised equipment operators, are used and the vessel has sleeping berths and living quarters to allow the vessel to have an operational endurance of up to a month.

Crew work 12-hour shifts with rotations month by month to enable a constant flow of data collection, processing, and interpreting.

What's in it

- Specialist crew
- Survey and analysis equipment

P.4.2 Geotechnical surveys

Function

Geotechnical site investigations are conducted following the geophysical survey to use the information obtained to target soil and rock strata boundaries, engineering properties and specific sea floor features.

What it costs

About £2.1 million for a 450 MW floating offshore wind farm.

Who supplies this

Fugro, G-tec, Gardline and Horizon Geosciences.

Key facts

Geotechnical studies are predominantly intrusive and include methods like drilling boreholes to collect soil and rock samples, and cone penetration testing (CPT).

Geotechnical investigation is generally the most expensive part of floating offshore wind farm survey work, making it a substantial at-risk investment for developers. Typically, the geotechnical surveys are performed in phases to add value to the project risk mitigation process.

Geotechnical surveys require specialised equipment and skilled personnel. The scope of the investigation depends on the type of foundation being considered and the variability in the sea bed characteristics.

Boreholes and CPTs are carried out to investigate the physical characteristics of the sea bed. Surface push CPTs are also used as a rapid method to gather sea bed soil stratigraphy. Cable routes are typically investigated using vibro-cores and CPTs to a depth of 5 m.

Offshore laboratories are used to obtain basic soil parameters and samples are taken there for detailed testing once they have been collected. Often soil dynamics tests are performed to monitor the soil behaviour under the constant dynamic loading on the foundation by the wind, waves and current.

Resultant data from the geotechnical surveys are combined with results from the geophysical survey, to improve the geological model prior to the design and installation of anchors. Geotechnical data is also used later in combination with heavy lift jack-up vessel information to determine the risks and feasibility of conducting heavy lift construction activities.

Fixed offshore wind farms require geotechnical data to depths of 50 to 70 m to inform the design of monopile or jacket foundations. Floating offshore wind farms use anchors which are typically not installed as deep as monopiles, although this does depend on the type and design of anchor selected (see B.3.1 for further information). This means that geotechnical surveys are generally needed to shallower depths for floating offshore wind farms compared to fixed.

In the early floating offshore wind projects, developers are expected to be cautious and conduct geotechnical surveys for every anchor placement. The sample and survey frequency may decrease in time as developers gain confidence and experience.

What's in it

- P.4.2.1 Geotechnical survey vessels

BVGAssociates

P.4.2.1 Geotechnical survey vessels

Function

Specialist vessels carry out geotechnical surveys of the sea bed.

Who supplies this

Fugro, G-tec, Gardline and Horizon Geosciences.

Key facts

The vessels are typically 60 to 100 m long and typically operate their drilling systems through a central moon pool. Some sea bed systems are deployed over the side or stern via A-frames or heavy lift cranes. The vessels are able to operate independently in remote locations.

Jack-up vessels can also be used (albeit smaller than those used for foundation and turbine installation) where water depth and sea bed conditions are suitable. The vessels must be able to position themselves at specific locations for borehole sampling using dynamic positioning or anchors and must be able to withstand unfavourable sea and weather conditions.

The vessels provide a stable platform for the acquisition of samples and in-situ testing. Due to the expense of hiring these vessels, multiple crews, including highly specialised equipment operators, are used and the vessels have sleeping berths and living quarters to allow the vessel to have an operational endurance of over a month.

Offshore laboratories also allow for data acquisition and processing onboard. Crew rotations month by month enable a constant flow of data collection, processing, and interpreting.

What's in it

- Specialist crew
- Survey and analysis equipment

P.4.3 Hydrographic surveys

Function

Hydrographic surveys examine the impact of the floating offshore wind farm development on local sedimentation and coastal processes such as erosion. This is often part of the geophysical survey. These surveys are also part of the post construction monitoring during the operations phase.

What it costs

About £800,00 for a 450 MW floating offshore wind farm.

Who supplies this

Specialist hydrographic survey companies: Fugro, Gardline and MMT.

Impact modelling consultants: ABPmer and HR Wallingford.

Key facts

Understanding the sedimentation environment of the proposed site is of particular importance as it informs the scour characteristics of the site and subsequent protection measures required.

What's in it

- Crews
- Survey equipment
- Vessels
- Analysis and reporting

P.5 Engineering and consultancy

Function

Front-end engineering and design (FEED) studies address areas of floating offshore wind farm system design and develop the concept of the floating offshore wind farm in advance of procurement, contracting and construction.

What it costs

About £4 million for a 450 MW floating offshore wind farm.

Who supplies this

Arup, DNV, Gavin & Doherty Geosolutions, Kent, Mott MacDonald, ODE, OWC, Ramboll, Wood and Worley.

Key facts

Earlier on in the process, concept and pre-FEED studies are used to develop an outline concept of the project for the purposes for defining the consent envelope and to inform environmental surveys.

The FEED study is continually refined through the development process and is ultimately used to inform substantial engineering and procurement decisions.

Key parameters such as turbine size, substructure type, mooring system design, wind farm layout, substation design, electrical system, and grid connection are considered in order to minimise project LCOE. Some projects consider integrating floating offshore wind turbines with co-located batteries, green hydrogen generation or the powering of oil and gas production facilities.

FEED studies also include the planning of onshore and offshore operations, port and vessel strategies, determining contracting methodologies and the development of key risk management and health and safety procedures.

The FEED study seeks to understand the total wind farm system in an integrated way and to consider the impact of engineering decisions on the LCOE, and to ensure that engineering decisions take full cognisance of environmental and consenting risks and impacts.

The FEED study is a multi-disciplinary process that requires extensive communication and coordination, often across multiple teams and organisations.

Engineers normally use industry-specific standards to guide the design process for components including, but not limited to, the floating substructure. The most complete standards for floating offshore wind are IEC 61400-3-2 and DNV-ST-0119. Other standards used on current floating offshore wind projects include ABS 195/206, NKRE-GL-FOWT01 and BV NI572.

The outputs of FEED studies are used to procure and construct the floating offshore wind farm.

The move to auction-based systems such as CfD in the UK has placed a greater emphasis on FEED studies as developers require greater cost certainty earlier in the development process.

Developers of early floating offshore wind projects are likely to conduct more detailed FEED studies, and hence incur higher FEED costs, because floating offshore wind project norms have not yet been established. The detail and cost of FEED studies will decrease as developers gain more experience and designs and operational practices become more established.

Project certification is an independent process used to give confidence to parties such as the developer's senior management, lenders or insurers, that the design, manufacture and installation of the whole project has been carried out to appropriate standards. It is not a regulatory requirement in the UK but is normally used for offshore wind projects. Certification schemes applicable to floating offshore wind include IECRE OD-502, DNV-SE-0190 and DNV-SE-0422.

What's in it

- Electrical design strategy
- Foundation type selection
- Health and safety planning
- Installation methods
- Interface management
- Layout design and optimisation
- Operational strategy
- Turbine selection

P.6 Project management

Function

This involves the management of various activities as part of wind farm development. This includes managing the collection and interpretation of surveys, submission of planning consents and any design work, and managing the construction of the project through to COD.

What it costs

About £20 million for a 450 MW floating offshore wind farm.

Who supplies this

Predominantly undertaken in-house by wind farm developers. The project management of specific activities can also be managed externally by consultancies or as part of EPCI contracts.

Key facts

Development phase project management includes end to end management of all surveys, assessments, design studies, stakeholder and supply chain engagement, and securing a route to market.

Construction phase project management includes the management of each of the different construction packages.

Financial project management includes the management of budgets, accounting, project financing, insurance, and the organisation of power purchase agreements (PPAs) and CfDs.

What's in it

- Securing a route to market
- Development phase project management
- Construction phase project management
- Financial management
- Stakeholder engagement

T Wind turbine

Function

The turbine converts kinetic energy from the wind into three-phase AC electrical energy.

What it costs

About £20 million for a 15 MW floating offshore wind turbine. This includes components, factory assembly and some elements of installation and commissioning, plus warranty provision. The elements of installation and commissioning included in this cost are mainly the supplier's logistics and staff costs at head office, at the construction port, on the installation vessel and on the turbine, mechanical and electrical completion, testing, and pre-handover checks and trouble shooting. These costs typically exceed £1.5 million per turbine.

Who supplies this

Western suppliers: GE Renewable Energy, Siemens Gamesa Renewable Energy (SGRE) and Vestas.

Asian suppliers: CSIC Haizhuang, Doosan, Dongfang Electric Corporation, Envision, Goldwind, Hitachi, MingYang, Shanghai Electric, Sinovel and XEMC Windpower.

Key facts

Most designs have upwind, pitch controlled, variable speed rotors with three blades. Compared to onshore wind turbines, offshore turbines are larger and there is an increased focus on reliability and maintainability and a decreased focus on noise, visual and transport constraints.

Floating offshore wind projects use the same turbine models that are used for fixed turbines, with minor variations:

- The control system tuned to jointly optimise the loads and energy production for the particular combination of turbine, floating substructure and metocean conditions.
- Tower stronger and heavier to compensate for the increased loads and different resonant frequencies experienced by the floating structure.
- Downwind variants have not been developed yet by the established suppliers by the established, as there is not yet enough demand.

Up to 2030, the ratings of turbines used on floating projects may lag a few years behind the turbines used on fixed offshore wind projects. This is because suppliers will want to have greater confidence in the response of each turbine model to the dynamic loads of the floating substructure before they are used on floating projects.

Wind turbine suppliers are systems integrators. Blades are typically manufactured in-house, along with a few other components in some cases, depending on the industrial strength and breadth of the supplier.

There are fewer offshore turbine suppliers than onshore turbine suppliers. The high investment costs, large project sizes but relatively low overall sales volumes make it difficult for new suppliers to challenge the incumbents.

Typically, after a new turbine model is developed, variants of this model are offered to the market with higher ratings and/or larger diameter rotors, whilst many of the original systems and components remain unchanged. These variants become possible once the loads and factors of safety are better understood. This extends sales lifetime of a given model while minimising development costs.

Wind turbine suppliers prefer to operate just one or two nacelle assembly facilities and blade manufacturing facilities for the European offshore market, to avoid adding complication and cost to their supply chains. The choice of site depends on the size of the local market, the locations of key suppliers, skills availability, and support for local job creation.

The design life of an offshore turbine is 25 years. The trend for longer design life on all turbines is due to the maturing of the industry. Asset owners now expect to operate wind farms for such periods without the technology becoming obsolete or unsupported by suppliers. The design driver for many components is fatigue loading when generating. Extreme loads due to storms, abnormal events and faults during operation can also be critical. Typically, an offshore turbine will be turning over 90% of the time.

Asian suppliers are typically offering turbines optimised to lower average wind speed wind regimes with larger rotors for a given turbine rating.

Type certification for turbines is provided by third parties. This confirms that the wind turbine type is designed, documented and key features of performance verified in conformity with specific standards and other technical requirements. This certification also covers the suppliers of the key components.

Health and safety requirements are encouraging safety by minimising or avoiding designs where people need to be put in hazardous environments.

What's in it

- T.1 Nacelle
- T.2 Rotor
- T.3 Tower
- T.4 Electrical system

T.1 Nacelle

Function

The nacelle supports the rotor and converts the rotational energy from the rotor into three-phase AC electrical energy.

Figure 12 GE's Haliade X 12 MW nacelle. *Image courtesy of GE Renewable Energy. All rights reserved.*

What it costs

About £11 million for a 15 MW floating offshore wind turbine.

Who supplies this

Nacelles are assembled by the wind turbine supplier, using components generally sourced from a range of external suppliers.

Key facts

Typical dimensions for a 15 MW turbine are 21 to 25 m long, 9 to 12 m wide and 10 to 12 m high for transport, with masses of 600 to 700 t including the hub.

Key nacelle components include the main bearing, gearbox (where used), generator, yaw bearing and yaw system.

The main bearing supports the rotor and transfers the rotor loading to the nacelle bedplate. Several bearing arrangements exist for offshore wind turbines including a single bearing supporting the generator and rotor. Another approach is to support the main shaft with a bearing at each end.

Where used, a gearbox converts rotor torque at a speed of 4 to 8 r/min to a speed of up to about 600 r/min for a medium speed gearbox. The gearbox is a critical item in the wind turbine drive train, with particular attention given to the long-term reliability.

There has been a move away from gearboxes with conventional high-speed generators for offshore turbines. For example, GE Renewable Energy and SGRE have opted for direct drive turbines without a gearbox. Instead, they use a larger and more complex low-speed generator. Vestas has opted for turbines with a gearbox and medium speed generator.

The generator converts mechanical energy to electrical energy. Most generators use permanent magnets that need no excitation power. This keeps efficiency high, mass low and dimensions small, lowering transport and installation costs but does rely on the supply of rare-earth alloys.

The yaw bearing connects the nacelle and tower, enabling the yaw system to turn the nacelle to any wind direction during operation. The yaw system orients the rotor and nacelle to the wind direction during operation.

Other nacelle components include the:

- Bedplate which supports the drive train and the rest of the nacelle components and transfers loads from the rotor to the tower
- Main shaft which transfers torque from the rotor to the gearbox or, for direct drive designs, the generator
- Control system which provides supervisory control (including health monitoring) and active power and load control in order to optimise wind turbine life and revenue generation, while meeting externally imposed requirements, and
- Condition monitoring system which provides additional health checking and failure prediction capability.

Nacelle mass is kept as low as reasonably possible to help with overall system dynamics and minimise logistics costs. To keep nacelle mass down, turbine designs may have the transformer and much of the power electronics in the tower base. Mid-grade steels and cast spheroidal graphite (SG) iron are used rather than low-grade materials as they offer the lowest cost per unit fatigue strength.

Before dispatch, the nacelle undergoes a functional test before being prepared for transport and storage. It is also typically tested with its power take-off hardware.

New designs of offshore turbines place a high emphasis on maintainability. This is being achieved through modular designs for large components so more subcomponents can be replaced using the nacelle crane. The use of jack-up vessels is not an option at depths suited to FOW.

The nacelle incorporates high levels of remote monitoring, health checking and control.

There are no major differences in the nacelles designed for floating or fixed offshore wind farms. Adjustments are needed to the control system to make the turbine suitable for application in floating.

What's in it

- Bedplate
- Condition monitoring system
- Control system
- Gearbox
- Generator
- Main bearing
- Main shaft
- Nacelle auxiliary systems
- Nacelle cover
- Small engineering components
- Structural fasteners
- Yaw bearing and actuator system

T.2 Rotor

Function

The rotor extracts kinetic energy from the air and converts this into rotational energy in the drive train.

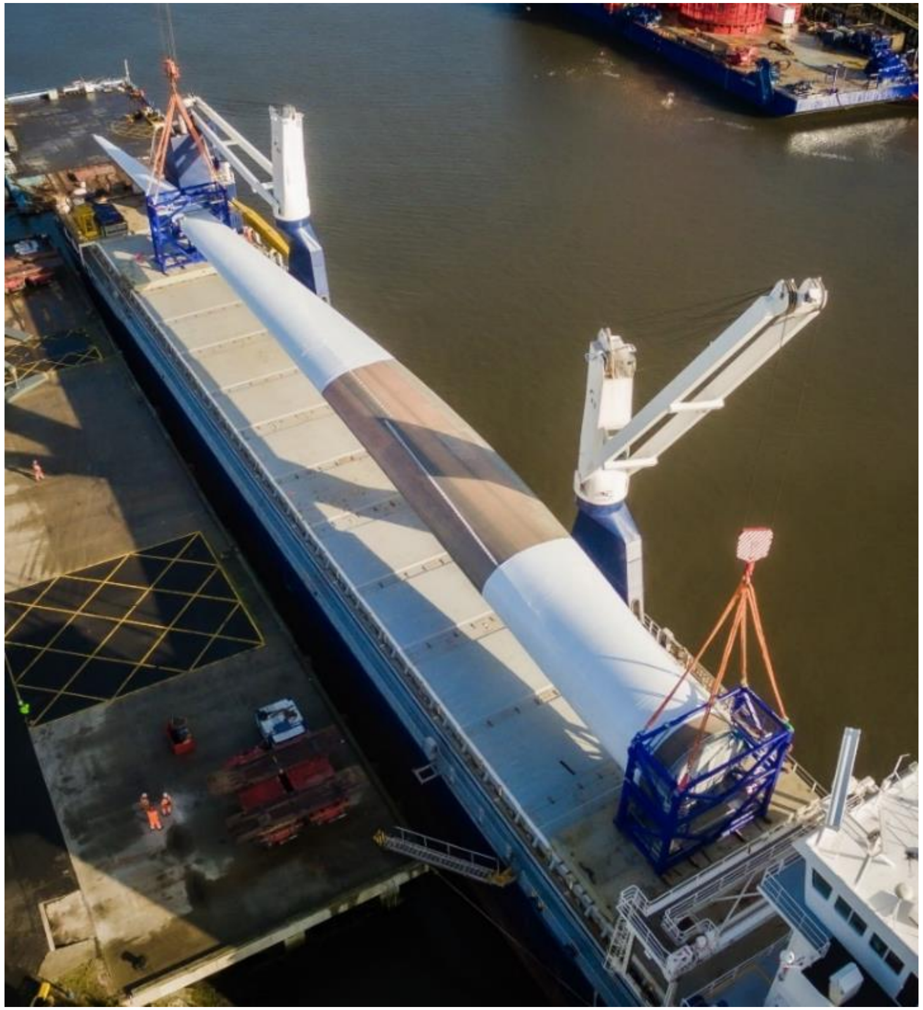

Figure 13 Example of an offshore wind turbine blade. ***Image courtesy of LM Wind Power.*** ***All rights reserved.***

What it costs

About £6 million for a 15 MW floating offshore wind turbine.

Who supplies this

Wind turbine rotors are usually designed and supplied by the wind turbine supplier as part of the complete wind turbine. Independent blade manufacturers are used by some wind turbine suppliers.

Key facts

A rotor for a 15 MW turbine has a mass of about 230 t and a diameter of about 224 m.

The rotor consists of blades, a hub casting, blade system, bearings, and pitch system.

Blades are typically made from fibreglass and epoxy resin. There are variations between designs, with some using carbon fibre and others using polyester resins. New resin systems are being developed and tested to enable the recovery and reuse of blade materials at the end of life.

Higher tip speeds typically lead to more efficient energy capture, and tip speeds offshore are higher than those used onshore, but these are limited by design to avoid blade leading edge erosion. This is where repeated impact by raindrops, particulate matter, hail, ice, and salt erodes the blades, causing surface roughness and change in aerodynamic shape to the outer part of the blade's leading edge. This reduces the performance of the blade and increases its sound emissions. If left unrepaired, the damage will continue until it affects the structural integrity of the blade.

Reducing the risk of leading edge erosion is an important focus for innovation. One approach is developing better coatings. Another is to incorporate leading edge protection plates similar to those used in helicopter blades that are flexible enough to cope with the deflections seen in wind turbine blades.

Each blade is bolted to a blade bearing that is bolted to a central hub on the main shaft. The blade bearing enables the pitch mechanism to adjust the blade pitch angle to control power output from the turbine, minimise loads and start or stop turbine as required.

Each blade has its own independent pitch system that allows the turbine to be controlled should one pitch system fail. Pitch systems are either hydraulically or electrically operated, with little external difference in functionality.

Typically, the blade pitch angle is adjusted almost constantly in medium-to-high winds to regulate rotor speed while the turbine is extracting maximum (rated) power. In lower winds, the pitch system operates to maximise aerodynamic efficiency, which requires substantially less movement.

There is potential for larger offshore wind rotors, though for the same design, mass increases faster than the additional energy generated. This is because energy capture is proportional to the two-dimensional swept area (square of blade length), but the blades increase in size and mass in three dimensions (cube of blade length). Substantial improvements in blade technology have kept the actual increase in mass nearer the square than the cube of blade length as wind turbines have increased in size.

Capacity factors of over 50%, are expected for 15 MW offshore turbines on good offshore sites. This compares with capacity factors of about 40% for good onshore sites.

As turbine rotor diameter increases, with the same limit on tip speed, the rotational speed decreases. Lower rotational speeds make it more difficult to design a support structure that avoids resonant frequencies excited by loading from waves and operation of the turbine itself.

Rotor speeds are 4 to 8 r/min, resulting in a maximum tip speed of over 100 m/s.

In the UK, rotor clearance must be at least 22 m above mean high water spring (MHWS) tides.

There are no major differences in the rotors designed for floating or fixed offshore wind farms.

What’s in it

- Blades
- Blade system and bearings
- Hub casting
- Pitch bearing and actuator system
- Rotor auxiliary systems

T.3 Tower

Function

The tower is typically a tubular steel structure that supports the nacelle. It also provides access to the nacelle, houses electrical and control equipment, and provides shelter and storage for safety equipment.

Figure 14 Offshore wind turbine towers being stored at the quayside of a port. *Image courtesy of TMS. All rights reserved.*

What it costs

About £3 million for a 15 MW floating offshore wind turbine.

Who supplies this

CS Wind, Gestamp Renewable Industries, GSG Towers, Haizea Wind Group, Titan Wind Energy, Windar and Welcon.

Key facts

Fabricators manufacture towers to designs provided by wind turbine suppliers, sometimes using free-issue materials (both steel and internal components).

Towers are normally made at coastal locations.

Once fabricated, the tower sections are shot-blasted, metal sprayed and painted before fit-out with other internal components then prepared for transport and storage.

The hub height is about 135 m above mean sea level minimum depending on the rotor diameter, so each tower is about 120 m high and has a mass over 800 t.

Towers on early stage floating projects have had almost double the mass of the towers of equivalent fixed offshore wind turbines. This is to cope with the increased loads and different resonant frequencies experienced by the floating structure (wind turbine and floating substructure) including excitation from wave loading. Improved floating foundation designs and wind turbine control algorithms could reduce this additional mass.

About 90% of the mass is steel plate with forged steel flanges making up most of the rest.

Towers are generally tapered, with a top diameter of about 6 m and a base diameter of about 10 m for a 15 MW turbine.

Design is driven by fatigue and extreme loading, plus natural frequency requirements and avoidance of bucking.

The optimum tower height is normally as low as is needed to comply with maritime safety regulations for blade clearance above the water. This is because the wind shear is low offshore (the wind speed does not increase significantly with increasing the hub height), meaning there is not enough cost benefit to use a taller tower. The tower height to achieve blade clearance does not need to take account of the tidal range for floating offshore wind turbines using semi-submersible floating substructures because they rise and fall with the tides. Permitting at some sites has required taller towers to reduce the risk of bird strikes.

Integrated design of substructures and towers is increasingly seen as desirable with the transition from substructure to tower predicted to be less distinct. The tower continues to be a discrete component supplied with the wind turbine.

Towers for floating substructures that yaw around a single mooring point, or have more than one rotor, have the potential to be significantly different from the established norm.

The tower internals provide means of access, lighting and safety for maintenance and service personnel, plus means of transferring hand tools and components to the nacelle. They provide support for control and electrical cables and housing of switchgear, transformers, and other elements of power take-off.

Tower internals also provide storage for survival equipment. A tuned damper may be located at the top of the tower to aide damping of tower and structure resonances.

What's in it

- Corrosion protection
- Tower internals
- Tower structure

T.4 Electrical system

Function

The electrical system receives electrical energy from the generator and adjusts voltage and frequency for onward transfer to the wind farm distribution system.

What it costs

The electrical system cost is included in that of the nacelle.

Who supplies this

Cables: Nexans, NKT and Prysmian.

Electrical components: ABB, AVK SEG, Crompton Greaves, GE Power Conversion, Ingeteam, S&C, Schneider Group, SGB, Siemens Power Transmission and Distribution and The Switch.

Key facts

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

Most wind turbines have variable speed generators connected to the array cables via AC-DC-AC power converters. There is a range of different generator/converter architectures used. With high power density, insulated-gate bipolar transistor (IGBT)-based power converters frequently are water-cooled.

Critical in the design of power converters are the requirements imposed by grid operators for wind turbines to support and stabilise the grid during grid faults and to provide or consume reactive power on demand (see B.4 and B.5 for further information). Some convertors may be split between nacelle and lower tower section to reduce tower head mass.

Where the turbine voltage rating does not match that of the wind farm array, transformers are often placed in the nacelle, or sometimes at the base of the tower. Typically, they transform from low kV (0.69 kV to 3.3 kV) to 66 kV for distribution around the wind farm array and must meet detailed corrosion, environmental and combustion requirements.

Converters and transformers are expected to be located at the tower base when the floating market is larger, as there is a higher premium on tower-head mass than for fixed offshore wind turbines.

Switchgear is designed specifically for wind turbine applications, for example gas-insulated for compactness and safety at up to wind farm distribution voltage.

Down-tower cabling is routed to enable the cables to twist, allowing the nacelle two complete revolutions of movement by the yaw system before an untwisting operation is required.

The only access to the inside of the tower base is via the access door, so if the transformer is mounted in the tower base, it is essential to be able to replace it via the door in case of failure.

If sensitive electrical systems are placed at the tower base, then these are protected by a local air conditioning system.

Electrical components and cables are generally supplied by the turbine supplier to the tower manufacturer for fit-out.

What's in it

- Cables
- Communications system
- Control system
- Power converter
- Transformer
- Switchgear

B Balance of plant

Function

The balance of plant includes all the components of the floating offshore wind farm except the wind turbines. It also includes the transmission assets built as a direct result of the wind farm.

What it costs

About £760 million for a 450 MW floating offshore wind farm.

Who supplies this

See relevant sections below.

Key facts

Much of the benefit of larger wind turbines on a wind farm is realised by the reduction in balance of plant costs per MWh, as larger wind turbines mean fewer structures and less cable.

Balance of plant costs for floating offshore wind farms are higher than for fixed offshore wind farms, mainly because of the increased substructure costs and more costly dynamic cables.

Balance of plant costs for floating offshore wind farms are lowest in water depths between approximately 100 and 150 m:

- Costs increase at greater water depths because of the increased mooring and cabling requirements, but this increase is not as pronounced as for fixed offshore wind farms.
- Costs also increase in water depths less than approximately 100 m, as floating substructure and mooring costs increase due to the interaction of waves with the sea bed at these depths.

What's in it

- B.1 Cables
- B.2 Floating substructure
- B.3 Mooring system
- B.4 Offshore substation
- B.5 Onshore substation

B.1 Cables

Function

The cables deliver the power output from the wind turbines to the transmission network.

What it costs

About £140 million for a 450 MW floating offshore wind farm.

Who supplies this

Hellenic Cables, JDR Cable Systems, LS Cable & System, Nexans, NKT, Prysmian, Sumitomo Electric and TKF.

There are other cable manufacturers based in China and Japan, but they have yet to be used widely for UK projects.

Key facts

Offshore wind farms use array cables to deliver power from the wind turbines to the offshore substation, and export cables to deliver power from the offshore substation to the onshore substation. Subsea cables are used for the array cables and the offshore section of the export cable. Onshore cables are used for the export cable section between the shore and the onshore substation.

A standard subsea cable used in offshore wind is made up of a stranded, profiled conductor with a combination of sealing layers, insulation, fillers, and protective armouring. Subsea AC cables have three cores (one for each phase). Onshore AC cables have single cores and are laid in groups of three. DC cables (land and subsea) have single cores (two, one positive and one negative, for each circuit).

There are three main insulated power core design types:

- Dry, with an extruded lead sheath over the insulation
- Semi-wet, with a polyethylene sheath over a non-fully impervious metallic screen, and
- Wet design, without a sheath over a non-fully impervious metallic screen.

Wet designs have the advantage of being lighter and more flexible. Currently, cables with voltages above 66 kV are only available as dry designs.

The terms for voltage ratings are not formally defined by the industry. Low voltage (LV) typically refers to cables rated up to 11 kV, medium voltage (MV) typically refers to cables rated up to 66 kV, high voltage (HV) typically refers to cables rated up to 220 kV and extra high voltage (EHV) typically refers to cables rated higher than 220 kV.

HV and EHV cables are generally associated with transmission networks and export cables, whereas MV is associated with array cables. The wind turbines generate at LV with a transformer at the base of the tower stepping up exported power to MV.

Cables have a specified minimum bend radius. Failure to maintain this during transportation, installation, and operation greatly increases the risk of damaging the cable, potentially leading to cable faults.

Floating offshore wind farms make extensive use of dynamic cables. These are designed to be exposed in the water column and to withstand the movement of floating substructures, subjecting them to greater fatigue loading than static cables. Compared to static cables, dynamic cables have:

- Sheathing over insulation using materials other than lead
- An additional layer of armouring, and
- Polyethylene outer sheath instead of polypropylene yarn.

Cable suppliers have invested significantly in dynamic designs to support the development of the floating offshore wind sector.

BVGAssociates

What's in it

B.1.1 Array cable

Function

The network of array cables transfers power from the wind turbines to the offshore substation. It also provides auxiliary power to the turbines when they are not generating and provides fibre communications.

Figure 15 Dynamic array cable. ***Image courtesy of JDR. All rights reserved.***

What it costs

About £32 million for a 450 MW floating offshore wind farm.

Who supplies this

Hellenic Cables, JDR Cable Systems, LS Cable & System, Nexans, NKT, Prysmian, Sumitomo Electric and TKF.

There are other cable manufacturers based in China and Japan, but they have yet to be used widely for UK projects.

Key facts

Array networks are most often designed as "strings" which connect several turbines to the substation. They can also be designed in loops to increase redundancy.

Each turbine is linked to the next with at least 1.5 km of array cable, assuming a 15 MW turbine with 224 m rotor diameter and seven times diameter spacing between turbines.

Array cables have a dynamic cable length between the sea bed and the floating substructures. The dynamic cable length typically follows a lazy wave configuration to accommodate dynamic movement of the floating substructure, including lateral excursion (the horizontal movement of a floating offshore wind turbine). It must also accommodate the loads resulting from the cable being exposed to the whole water column, as well as withstanding abrasion from the sea bed. At the sea bed, the cable is either buried or sits on the sea bed anchored using rocks or protective matting (see I.2 for further information).

The dynamic section of array cable for floating offshore wind farms is incorporated in one of three ways:

1. A single length of dynamic cable between turbines
2. Dynamic lengths at each turbine connected to a static length in between using either field joints or connectors, or
3. A single cable assembly using dynamic cable at each end with a length of static cable in between, assembled using factory joints (so manufactured and installed as a single length of cable).

The final choice depends on the trade-off between the relative costs of static and dynamic cables, the additional costs of using field joints or connectors, and the introduction of additional potential points of failure at field joints or connectors.

In deep water array cables could be suspended across their whole length. This would put greater loading on the cable due to water current-induced movement of the cable but would reduce the length of cable required. Floating projects to date have not used this approach so the water depth at which this becomes attractive is not well understood, but it is likely to be in water depths of around 500 m.

Array cables are typically rated at 66 kV. In the next few years, array cable voltages are expected to increase to 132 kV. This is to accommodate more efficiently turbines rated at and above 16 MW and to reduce the number of array cable strings required.

Array cables are typically supplied by the manufacturer with cable accessories, although the production of accessories may be outsourced. Cable protection may be included in the array cable supplier's scope, but it is more often part of the installer's scope.

Some larger cable manufacturers have cable installation equipment and vessels (see I.2 for further information), but EPCI array cable packages have typically been led by marine contractors.

What's in it

- B.1.1.1 Array cable core

- B.1.1.2 Array cable outer

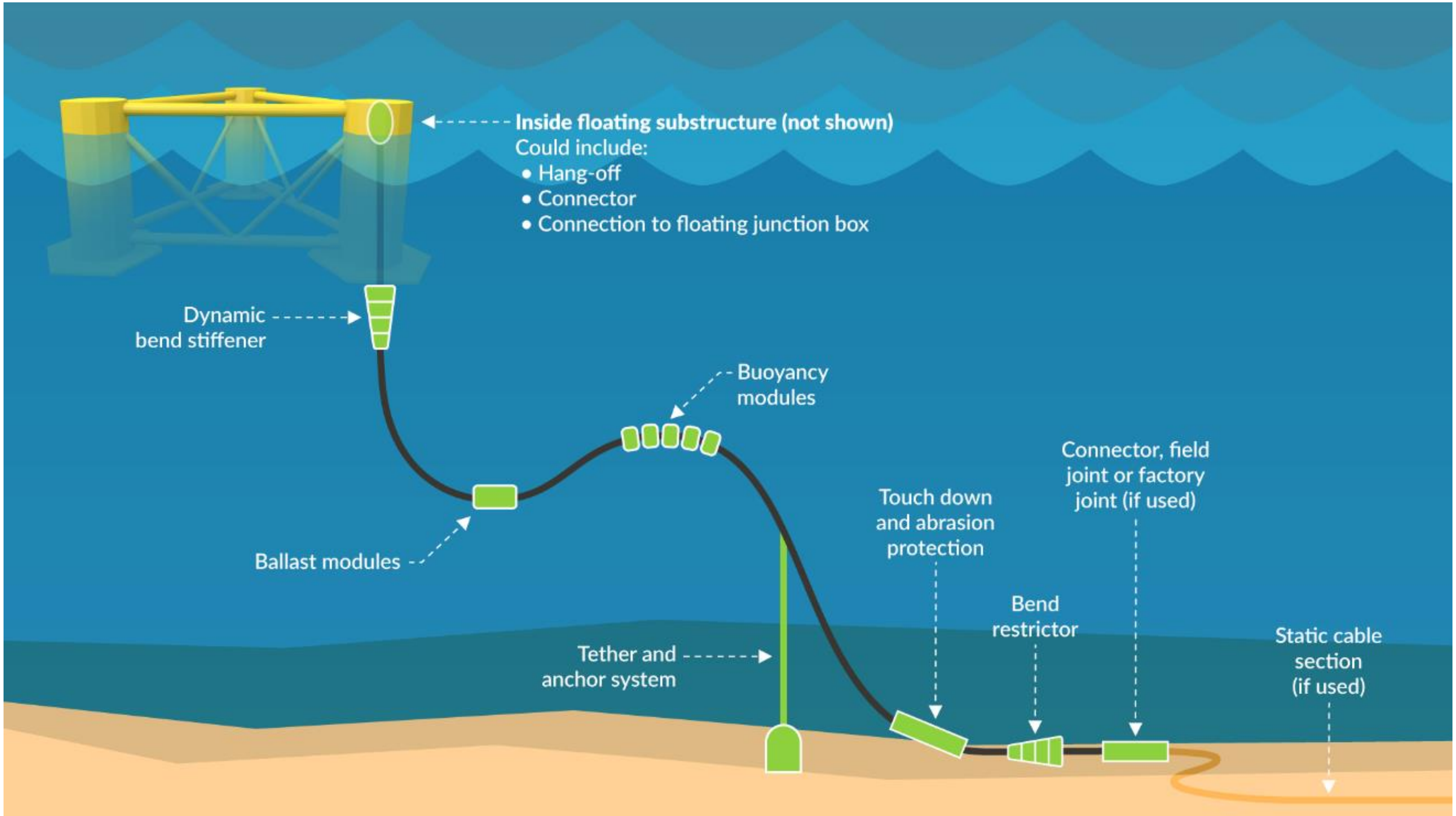

Figure 16 Floating offshore wind dynamic cable system. An actual system would not use all of these elements at the same time. The horizontal distance between the floating substructure and the touchdown point is typically around 200 m*. Image courtesy of BVG Associates. All rights reserved.*

B.1.1.1 Array cable core

Function

The cable core contains the conductor through which power is transferred. The rest of the core consists of screens, insulation, and sheathing to protect the conductor and prevent short circuits.

Who supplies this

Cable cores are typically manufactured by the cable manufacturer. Usually, complete cable cores are manufactured and assembled at the same site to reduce transportation costs of the different components.

Key facts

The conductor may be stranded copper or aluminium. Both have low resistance, excellent conductivity, are ductile, and are relatively resistant to corrosion. Copper has a higher conductivity, 60% greater than aluminium for the same cross section, but is more expensive and the price is more volatile. Aluminium is lighter, and therefore easier to handle.

Copper has better fatigue performance than aluminium, and small diameter strands have greater flexibility (hence resistance to fatigue) than larger strands. These are important considerations for the dynamic array sections.

The conductor screen is a semiconducting tape that surrounds the conductor, maintains a uniform electric field, and minimises electrostatic stresses on the cables.

Most subsea cables used in offshore wind are insulated with cross-linked polyethylene (XLPE). This is due to its excellent strength and rigidity. Ethylene propylene rubber (EPR) has also been used for array cable insulation. It is more flexible than XLPE but has higher dielectric losses.

Surrounding the insulation is a further screen, similar to the conductor screen.

Lead has historically been used for sheathing static subsea cable, but it does not have the fatigue resistance to cope with the additional mechanical stresses placed on cables in a dynamic environment. Alternatives are being researched to develop HV dynamic cables. Environmental concerns around the use of lead are also driving research into alternative sheathing materials. MV 66 kV cables can be wet-designed and so do not require water-blocking barriers.

The cable should at least have a conductor cross-section adequate to meet the system requirements for power transmission capacity. Energy losses can be reduced by using a larger conductor with a greater current carrying capacity but at a greater capital cost.

A 66 kV AC subsea cable conductor typically has a cross-sectional area of between 150 mm^2 and 800 mm^2 with 13 mm of insulation.

What's in it

- Conductor
- Conductor screen
- Insulation screen
- Sheath
- XLPE insulation

B.1.1.2 Array cable outer

Function

The cable outer surrounds the core and contains materials to protect the cable and house the fibre optic cable.

Who supplies this

Materials: Commodity suppliers.

Fibre optic manufacturers: Hexatronic and Huber+Suhner.

Fibre optic jointers and systems: Aceda and CCL UK.

Key facts

For a three-core cable, the cores are surrounded by non-conductive filling and packing material made from polypropylene. Its purpose is to maintain the cable's shape and structure. All are then bound together with tape into a single cable.

A layer of polypropylene string is applied over the assembly as bedding for the armour wires.

The armouring is usually made up of helical metal wires surrounding the cable. Armouring wires are usually made from either stainless steel or non-magnetic galvanised steel. The choice of armouring is important as impacts the cable's protective, handling, and electrical properties.

Dynamic cables require two layers of armouring, compared to a single layer for static cables. This is to provide the cable with additional fatigue resistance.

Bitumen may be applied over the armouring to protect against corrosion and to provide additional adhesion.

Static cables use a layer of polypropylene yarn over the armour, to provide resistance to abrasion and to reduce friction during laying. It is applied with a black and yellow pattern to make the cable visible during laying.

Dynamic cables use a polyethene sheath on the outer layer rather than polypropylene yarn. This is to provide additional fatigue resistance to the cable.

At least one fibre optic cable is integrated into the power cable for communications. The cable is multimodal, meaning that it can carry a wide range of data at different frequencies, typically for voice, turbine, switchgear, condition monitoring and security information. A fibre optic cable typically has 48 strands.

What's in it

- Armouring wire
- Bitumen
- Fibreoptic cable
- Polypropylene yarn

B.1.2 Export cable

Function

The export cable connects the offshore and onshore substations to transmit power from the wind farm to shore. It also provides auxiliary power to the wind farm when it is not generating and provides fibre communications.

Figure 17 Static export cable. ***Image courtesy of JDR. All rights reserved.***

What it costs

About £88 million for a 450 MW floating offshore wind farm with cable lengths described in Table 1.

Who supplies this

Hellenic Cables, LS Cable & System, Nexans, NKT, Prysmian and Sumitomo Electric.

There are other cable manufacturers based in China and Japan, but they have yet to be used widely for UK projects.

Key facts

As dynamic export cables are not yet proven, fixed offshore substations with static export cables are expected to be used for early floating projects, and this is the scenario described in this report.

Floating offshore wind farms using floating offshore substations will require a dynamic section of export cable. This is connected at the sea bed to a static length of export cable, which will run the majority of the cable length to shore.

Soon after landfall, the subsea export cable is jointed to the onshore export cables in a transition joint bay (see I.3 for further information). Onshore export cables run from the transition joint bay to the onshore substation. Onshore export cables are manufactured and laid as single-core cables, meaning that three individual onshore cables are jointed to a subsea three-core cable.

High voltage alternating current (HVAC) export cables are now typically rated at 220 kV, allowing the export of approximately 300 MW per three-core subsea cable. Future wind farms may use higher voltages of up to 275 kV. The voltage chosen balances the cost of the cable, the number of circuits required, and the number of offshore substations required. Wind farms tend to have more than one export cable circuit for redundancy.

Medium voltage alternating current (MVAC) cables may be used for export for small wind farms close to shore. Their use for commercial-scale projects in the future is therefore unlikely, but MV export is attractive for demonstration projects.

High voltage direct current (HVDC) connections are used to connect larger projects, typically those of more than 1 GW installed capacity, and those located further from shore, typically further than 80 to 100 km. For example, there are already 10 HVDC substations operating in German waters. Floating projects that are large and/or located far from shore are also expected to use HVDC connections.

HVDC significantly reduces losses caused by high levels of reactive power that is seen in long distance HVAC cables, which increases the net annual energy production. The full capacity of the cable system can be used for transferring active power because there is no reactive power flow in DC systems and the current flows at a constant level rather than fluctuating as a sine wave.

HVDC converter stations are expensive, and the savings from the use of HVDC cable are not realised until the cable route between the substations is 80 to 100 km. Even beyond 100 km, project-specific considerations can make the final choice complex in deciding between HVAC and HVDC. New technology is steadily reducing the cost of HVDC.

A subsea HVAC export cable is a three-core design, whereas a typical subsea HVDC system has a bipolar design with two single-core cables, a positive and a negative. For a given capacity, HVDC cables are lighter with positive implications for the ease and cost of installation. This is because the voltage is at a steady maximum - it is not at a lower average value because it is alternating - and none of the cable's capacity is taken up by carrying reactive power. Overall export cable costs, therefore, for an HVDC offshore wind farm are usually lower than for an HVAC wind farm.

The first commercial scale HVDC projects in UK, for example the fixed Dogger Bank projects, are using 320 kV export cables. A pair of single-core 320 kV cables can export up to 1,200 MW per pair. In time, the voltage may increase to 525 kV for even larger projects.

A static 220 kV three-core copper AC export cable has a mass of approximately 110 kg/m.

Two static 320 kV single-core copper DC export cables have a mass of approximately 80 kg/m.

HV dynamic export cables are not yet available but are the subject of industry research.

Several cable manufacturers have cable installation equipment and vessels (see I.2 for further information) and typically lead export cable EPCI packages.

What's in it

- B.1.2.1 Export cable core
- B.1.2.2 Export cable outer

B.1.2.1 Export cable core

Function

The cable core contains the conductor through which power is transferred. The rest of the core consists of screens, insulation, and sheathing to protect the conductor and prevent short circuits.

Who supplies this

Cable cores are typically manufactured by the cable manufacturer. Usually, complete cable cores are manufactured and assembled at the same site to reduce the transportation costs of the different components.

Key facts

An export cable core has the same components as an array cable core and uses mostly the same materials.

HVAC and HVDC export cables are also typically insulated with XLPE. HVDC systems have traditionally used mass impregnated cables with paper-based insulation as they can be manufactured and installed in long lengths and are available at higher voltages. Modern HVDC cables mostly now use XLPE insulation as XLPE can operate at a higher temperature and are lighter so easier to handle during installation.

A 220 kV AC subsea cable conductor typically has a cross-sectional area of between 800 mm^2 and 1,600 mm^2 with 23 mm of insulation.

A 320 kV DC cable conductor typically has a cross-sectional area of between 1,000 mm^2 and 2,500 mm^2 with 25 mm of insulation.

What's in it

- Conductor
- Conductor screen
- Insulation screen
- Sheath
- XLPE insulation

B.1.2.2 Export cable outer

Function

The cable outer surrounds the core and contains materials to protect the cable and house the fibre optic cable.

Who supplies this

Materials: Commodity suppliers.

Fibre optic manufacturers: Hexatronic and Huber+Suhner.

Fibre optic jointers and systems: Aceda and CCL UK.

Key facts

An export cable outer has the same components as an array cable core and uses the same materials.

What's in it

- Armouring wire
- Bitumen
- Fibre optic cable
- Polypropylene yarn

B.1.3 Cable accessories

Function

Cable accessories provide electrical termination and mechanical support for cables both during and after installation.

What it costs

About £20 million for a 450 MW floating offshore wind farm.

Who supplies this

See details of individual components below.

Key facts

Array and export cable systems require a range of different accessories to connect cables to structures, protect cables at vulnerable locations, maintain dynamic cable configurations, and connect lengths of cable together.

Cable accessories are usually included in either the cable supply or cable installation scope.

What's in it

- B.1.3.1 Interface
- B.1.3.2 Cable protection
- B.1.3.3 Buoyancy
- B.1.3.4 Connectors and joints

B.1.3.1 Interface

Function

Cables require several different products at the floating substructure and offshore substation interfaces.

Figure 18 Cable hang-off clamp and cable pull-in head. *Images courtesy of Tekmar and Oceaneering. All rights reserved.*

What it costs

About £4 million for a 450 MW floating offshore wind farm.

Who supplies this

Balmoral, MacArtney, Oceaneering, Subsea Energy Solutions, Tekmar and WT Henley.

Key facts

Hang-off clamps are installed where the cable connects to the floating substructure (dynamic hang-offs) and the offshore substation (static hang-offs). Hang-off clamps ensure the cable is mechanically secured after installation, to make certain that the mechanical stresses are safely borne by the cable armouring and not by the core.

Pull-in heads enable the safe installation of the cable to a floating or fixed foundation (see I.2.5 for further information). They typically connect directly to the cable armouring to ensure that all mechanical forces associated with pulling the cable are borne by the armour rather than the core. They are usually made from machined steel and are hot dipped galvanised and zinc plated.

Terminations connect the cable conductors to the electrical switchgear above the hang-off assemblies. Terminations connect to inline or T-connectors at the switchgear.

Cable tubes (J-tubes or I-tubes) route the cables from the outside to the inside of floating substructures and substation foundations and protect the cables from wave action.

What's in it

- Cable connectors, T-connectors
- Cable cleats
- Cable trays
- Hang-off clamps
- Interface plugs

B.1.3.2 Cable protection

Function

Cable protection helps to preserve the cables at vulnerable locations from wave and tidal action. For dynamic cables, this is typically where the cable enters and exits floating substructures and offshore substations, the touch down point, and where the cable lies exposed on the sea bed.

Figure 19 Cable bend stiffener. *Image courtesy of Kaylan Offshore. All rights reserved.*

What it costs

About £7.7 million for a 450 MW floating offshore wind farm.

Who supplies this

Balmoral, CRP Subsea, First Subsea, MacArtney, Subsea Energy Solutions, Tekmar and WT Henley.

Key facts

Cable protection systems ensure the cable is not subjected to excessive loading along the cable route.

Bend stiffeners and bend restrictors reduce the bending moments applied to cables. Connection points between cables and floating substructures use dynamic bend stiffeners. These are conical devices that limit the movement of the cable to a permitted range (dependent on the cable's minimum bend radius). Connections between cables and fixed structures (including fixed offshore substations or the sea bed) use static bend restrictors. These are rigid devices that force the cable to follow a constant bend radius to prevent overbending.

Dynamic cables can also require tether and anchor systems to reduce the movement of the current loading on the dynamic cables at the touch down point.

Abrasion protection and touch down protection are provided by protection matting and protection sleeves. These protect the cable where it lies exposed on the sea bed, where it enters or exits the sea bed, or where it crosses other cable routes.

What's in it

- Abrasion protection
- Bend restrictors
- Bend stiffeners
- Tether and anchor systems
- Touch down protection

B.1.3.3 Buoyancy

Function

Buoyancy and ballast modules are required to maintain certain cable shapes in the water column to reduce cable fatigue from the movement of the substructure. An example is the “lazy wave”.

Figure 20 Buoyancy modules stored on a vessel prior to installation. ***Image courtesy of Balmoral. All rights reserved.***

What it costs

About £2.5 million for a 450 MW floating offshore wind farm.

Who supplies this

Balmoral, CRP Subsea, DeepWater Buoyancy, SBT Energy and Tekmar.

Key facts

Buoyancy and ballast modules hold the dynamic cable in its designed shape, to reduce cable fatigue. Buoyancy modules are attached to points of the subsea cable to provide uplift, which reduces tension in the cables and maintains wave configurations. Ballast modules provide weight to points of the subsea cable for damping stability.

Buoyancy and ballast modules are both typically clamped to the outside of the cable during installation (see I.2 for further information).

What’s in it

- Ballast modules
- Buoyancy modules

B.1.3.4 Connectors and joints

Function

Connectors are pluggable connections between two segments of cable or between the cable and a floating substructure.

Joints are fixed connections between two segments of cable.

Figure 21 Dry mate connector and wet mate connector. *Images courtesy of MacArtney. All rights reserved.*

What it costs

About £5.8 million for a 450 MW floating offshore wind farm.

Who supplies this

First Subsea, MacArtney, Pfisterer, Power CSL, SBT Energy and Subsea Energy Solutions. Factory joints are installed in-house by cable manufacturers during the manufacturing process.

Key facts

Connectors allow cables to be disconnected and reconnected and can either sit on the sea bed or on the floating substructure.

They can be either dry mate or wet mate. Dry mate connectors are a mature and proven technology, but the connection must take place out of the water, usually on board a vessel or the floating substructure. Wet mate connectors can be disconnected and reconnected underwater but are not currently available at 66 kV and are a current area of research.

Not all floating offshore wind farms require connectors, and this is largely depend on the maintenance strategy of the developer. Disconnection of the floating substructure and the dynamic cabling system is required for a tow-to-port maintenance strategy meaning that connectors could be beneficial. Once 66 kV wet mate connectors have been developed and proven for array cables, they are likely to be used at each turbine for projects using a tow-to-port maintenance strategy. An in-situ maintenance strategy allows the turbine-floating substructure assembly to remain in place and so connectors may not be required.

Floating substructure designs that pivot downwind of a turret require a rotating connector.

Cable joints typically sit on the sea bed. There are two types:

- A factory flexible joint connects individual segments of cable core into one continuous length during the lay-up process. Crucially, the joint must have the same electrical, mechanical, and thermal properties as the rest of the cable and result in a joint that does not hamper installation or increase the risk of cable failure.
- A field rigid joint is a manufactured product. It may be supplied to the wind farm owner or the offshore transmission owner (OFTO) with the cable in case of failure during operation or supplied as a planned joint to link sections of cable. In floating offshore wind farms field rigid joints could be used to connect dynamic and static array cable sections, or to connect dynamic and static export cable sections if a floating offshore substation is used.

Field rigid joints have generally been bespoke products because of the substantial variations in cable design between wind farms. There is growing interest, particularly by OFTOs, in developing joints that are suitable for a range of cable designs.

What's in it

- Dry mate connectors
- Factory joints
- Field rigid joints
- Wet mate connectors

B.2 Floating substructure

Function

The floating substructure provides buoyancy to the turbine and, in conjunction with the mooring system, maintains the turbine's verticality and movements within acceptable limits. It also provides secondary functions of allowing access from vessels and accommodating ancillary equipment.

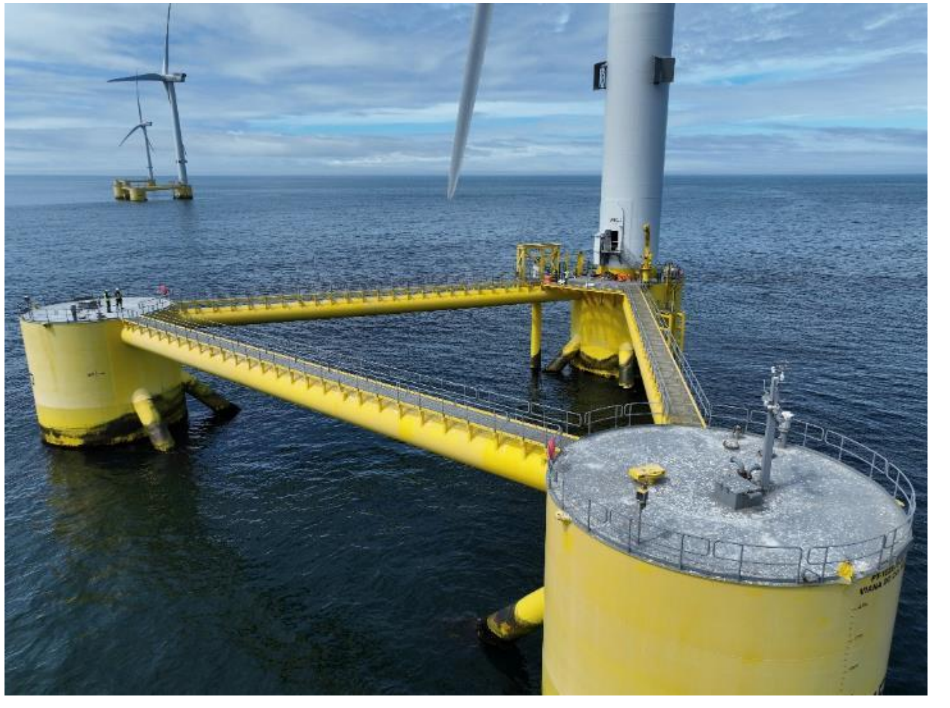

Figure 22 Semi-submersible floating substructures used at the WindFloat Atlantic project. ***Photo of the WindFloat Atlantic project courtesy of Principle Power/Ocean Winds.***

What it costs

About £430 million for a 450 MW floating offshore wind farm.

Who supplies this

Floating innovators: BW Ideol, Principle Power, Saitec, SBM Offshore and Stiesdal.

Engineering consultants: Kent and Ramboll.

Project developers: Equinor.

Steel fabricators: Bladt, EEW, Eiffage, Harland & Wolff, Lamprell, Navantia, Sif, Smulders and Welcon.

The contract for supply may be directly with the steel fabricator, or it can be through an EPCI contractor such as Aker Solutions, DEME, or Jan de Nul.

Key facts

There are four main types of floating substructures:

- Semi-submersible
- Barge
- Spar buoy, and
- Tension leg platform (TLP).

Semi-spar is the term sometimes used to describe a semi-submersible with a suspended mass to provide additional stability. In this Guide, it is considered to be a subset of semi-submersibles.

This section of the Guide describes a steel semi-submersible with three columns because this type is the most developed type to date.

A typical steel semi-submersible for a 15 MW turbine has an unballasted mass of about 3,500 t and dimensions of about 80 × 90 × 35 m.

The substructure can move along three axes (heave: up/down, sway: right/left, and surge: forwards/backwards) or rotate about three axes (pitch: tilt from front to back, roll: tilt from side to side, and yaw: rotate when seen from above). Accelerations from all six degrees of freedom contribute to the loads on the wind turbine, so it is vital that the substructure (in combination with the mooring system) controls these to within acceptable limits for a range of metocean and wind turbine load cases.

Once the wind turbine and the substructure type have been selected, a process of jointly optimising the substructure, mooring system, wind turbine and its control algorithms is carried out. Joint optimisation is a complex process and takes many months, but it is expected to shorten with experience.

Designs are based on those used successfully in the oil and gas market, but significant developments have been necessary to address the different loads and requirements of floating offshore wind turbines, and to optimise for serial manufacturing, installation, and support operations.

The diverse fabrication requirements and the logistical challenges of producing such large structures in volume may result in supply from several different locations or suppliers, with the final floating substructure assembly at the wind farm construction port.

The high labour requirements of floating substructures, particularly concrete designs, may make them an attractive opportunity for providing local content.

What's in it

- B.2.1 Primary structure
- B.2.2 Secondary steel
- B.2.3 Substructure auxiliary systems
- B.2.4 Corrosion protection

B.2.1 Primary structure

Function

The primary structure consists of the large structural elements which provide buoyancy and resist the loads from the mooring system and the base of the wind turbine tower.

Figure 23 The final assembly of the primary structure of a steel semi-submersible floating substructure. *Photo of the WindFloat Atlantic project courtesy of Principle Power/Ocean Winds.*

What it costs

About £360 million for a 450 MW floating offshore wind farm.

Who supplies this

Large steel or concrete floating substructures and their major components must be produced by specialists capable of fabricating large and heavy items, which requires the manufacturing facility to be located port-side. If the final assembly of the floating substructures is in a different location this must also be located port-side to move complete substructures into the water. Experience in batch volume production is highly desirable for orders of many units, which limits the choice of supplier options.

Fabricators: Aker Solutions, Bladt, EEW, Harland & Wolff, Lamprell, Navantia, Sif, Smulders and Welcon.

Key facts

The primary structure is made of the following main components:

- Columns
- Pontoons
- Trusses, and
- Transition piece.

Semi-submersibles typically have a triangular arrangement, with three columns connected by horizontal pontoons at the base, with further trusses (also known as braces) between them. The major structural elements are:

- Columns and pontoons: provide most of the buoyancy, and because they are located away from the centre of the substructure, they provide stability. The pontoons may have square edges and heave plates to reduce heave motion (up and down) in the water by creating drag.
- Trusses: the triangular shapes made by trusses, in conjunction with the columns and pontoons, provide rigidity.

- Transition piece: some designs include a transition piece to distribute the concentrated loads from the base of the tower into the floating substructure.

On a semi-submersible substructure the turbine may be positioned on one corner, in the centre, or halfway along one of the sides. A centrally-mounted turbine results in the most symmetrical loading and reduces the need for active ballasting to maintain verticality. A disadvantage is the longer crane reach needed to assemble the turbine onto the substructure.

Important considerations for efficient manufacturing include the space required, the cycle time (a shorter cycle time allows a higher delivery rate), and the total manufactured cost.

Some designs seek to use manufacturing processes and facilities developed for other purposes to reduce manufacturing costs, like tubular fabrication used for turbine towers (for example Stiesdal Offshore's TetraSpar) or panel production lines used for shipbuilding (for example Gusto MSC's Tri-Floater). The latter may result in columns with square or hexagonal cross-sections.

Some designs are fully welded whereas others use joints for the final assembly of the major items of the floating substructure. A design suited to final assembly allows manufacturing firms to focus on major component manufacture and suitably located ports to focus on the final assembly of the floating substructure.

The mass of a typical primary structure, at 3,500 t, is greater than the maximum lift capacity of the largest mobile cranes. Rail systems or self-propelled modular transporters are options for moving them on land. Ring cranes, vessel-mounted cranes, or semi-submersible barges can be used to move a primary structure from land into the water. A dry dock addresses both issues at the same time, but large dry docks are scarce (see I.5 for further information).

Some fabricators are exploring the use of electron beam welding to reduce the time, cost, and energy consumption associated with the more commonly used submerged arc welding.

What's in it

- Castings, for complex structural joints
- Forged rings, for the flange to the base of the turbine
- Prefabricated box sections
- Prefabricated steel tubes
- Steel plate - sometimes purchased cut to shape with its edges profiled to make fabrication easier; larger plate sizes reduce the total amount of welding needed

B.2.2 Secondary steel

Function

Provides access to, from, and within the substructure for personnel and equipment. Accommodates ancillary equipment.

Figure 24 Secondary steel elements on the floating substructures used at the Kincardine project. *Photo of the Kincardine Offshore Wind Farm project courtesy of Principle Power.*

What it costs

About £30 million for a 450 MW floating offshore wind farm.

Who supplies this

Hutchinson Engineering, Kersten, Smulders, Vallourec and Wilton Engineering.

Key facts

The mass of secondary steel in a 15 MW steel semi-submersible is approximately 100 t.

Examples of secondary steel components include:

- Boat landings
- Personnel access ladders
- Work platform
- Internal platforms and walkways
- External walkways
- Baffles to control the movement of water (ballast) and noxious gases (due to internal component corrosion), and
- Support structures for sacrificial anodes.

Secondary steel is normally subcontracted to a fabricator which does not have the high overhead costs of the fabricator of the primary structure.

Advances in personnel access systems, such as walk-to-work gangways or systems which lift personnel from a vessel, may avoid the need for boat landings.

Aluminium, fibre glass, or concrete may be used instead of steel for some components. For example, pre-cast concrete work platforms are used for some fixed offshore wind projects.

What's in it

- Floorplates
- Railings
- Welded steel structures fabricated from smaller steel sections and plates (these are frequently galvanised and painted)

B.2.3 Substructure auxiliary systems

Function

The substructure auxiliary systems support the substructure to provide its primary function and ensure compliance with regulatory requirements.

What it costs

About £26 million for a 450 MW floating offshore wind farm.

Who supplies this

Ballast systems: Seaplace.

Condition monitoring sensors: HBM and Strainstall.

Davit cranes: Granada, Palfinger Marine and Protea Group.

Navigation lights and markers: Oxley and Sabik Offshore.

Personnel winching systems: Limpet Technology and Pict Offshore.

Key facts

Auxiliary systems include:

- Ballast system, to pump sea water into or out of the floating substructure.
- Davit crane, for lifting modest loads on and off vessels.
- Personnel winching systems.
- Navigation lights and markers.
- Condition monitoring sensors, such as strain gauges, accelerometers, tilt and water level sensors.
- Small light and power for the above-mentioned systems.

Ballast makes a semi-submersible floating substructure sit lower in the water which increases its stability. Ballast may be added in steps, for example, first to achieve sufficient stability for the final assembly of the wind turbine, then for towing to the site, and finally for wind turbine operation. Some designs of semi-submersible use a large mass suspended by chains, rather than water.

An active ballast system maintains the verticality of the tower, taking account of the eccentric positioning of the turbine on the substructure and the overturning moments caused by the interaction of the wind with the wind turbine, which vary with wind speed and direction. As the active ballast system may fail, the substructure and mooring system need to be designed to cope for failure load cases. Not all floating substructure designs require active ballast systems.

While it is convenient to have equipment in place offshore for when it is needed, some types of equipment need to be periodically inspected, otherwise, they cannot be used (see O.2.3 for further information). There is a trade-off, therefore, to determine what is worth installing offshore, for example lifting equipment.

Information from condition monitoring sensors is used in the short term to validate design models and predict lifetimes. In the future, this information has the possibility of being used within control systems to actively manage loads.

What's in it

- Various marine “catalogue items” configured into systems. Some, such as davit cranes, are similar to those used for fixed offshore wind

B.2.4 Corrosion protection

Function

One or more forms of corrosion protection can be used to protect the substructure from corrosion to the extent that is required, such as a paint barrier with cathodic protection.

What it costs

About £22 million for a 450 MW floating offshore wind farm.

Who supplies this

Cathodic protection systems: Corrosion, Imenco, Impalloy and Metec Cathodic Protection.

Corrosion protection coatings: Hempel, Hutchinson Engineering, International Paint and Jotun.

Key facts

In offshore wind, corrosion predominantly occurs when sea water interacts with metallic surfaces. This can lead to oxidation (or rusting) of metallic surfaces, which can compromise the strength and performance of metal structures such as substructures. Corrosion protection mitigates general and localised wall loss in steel substructures and is a prerequisite for attaining the fatigue of the structure. Corrosion can also occur from microbiological activity.

Methods for corrosion protection include corrosion protective coatings and cathodic protection. The in-built corrosion resistance of the material and allowing an additional material thickness for corrosion are also considered.

The external surfaces of the atmospheric and splash zones are normally coated with high performance marine coatings that reduce corrosion.

Parts of the substructure in the submerged zone use cathodic protection systems to provide corrosion protection. The application of a negative current to the steel structure reduces the voltage on the structure to a level at which oxidation, and hence corrosion, is suppressed. There are two types of cathodic protection systems:

- Galvanic anode cathodic protection systems (GACP) comprise several sacrificial anodes made of aluminium or zinc-based alloys that are fixed to the steel structure below the waterline. These can be designed to be replaced periodically to extend the lifetime of the corrosion protection.
- Impressed current cathodic protection systems (ICCP) use an external power source and rectifier to supply a negative current to the steel structure and a corresponding positive current to non-consumed anodes mounted adjacent to the structure. An ICCP is substantially lighter and causes less drag in the water than GACP but requires a reliable power supply and additional instrumentation.

The chemical reactions that cause corrosion can generate noxious gases which accumulate inside a floating substructure. The lower deck of the substructure is sealed for the safety of maintenance technicians working above, whilst gas detection and ventilation systems may be used to monitor and safely vent the concentrations of the gases.

In closed internal structural compartments of the floating substructure which are welded shut, corrosion may be mitigated by humidity control or oxygen depletion.

What's in it

- Impressed current cathodic protection systems
- Paints and thermal metal spray coatings
- Zinc or aluminium based sacrificial anodes

B.3 Mooring system

Function

The mooring system provides the station keeping capability for the floating offshore wind turbine and contributes to the stability of the substructure and turbine.

What it costs

About £80 million for a 450 MW floating offshore wind farm.

Who supplies this

Bridon-Bekaert, Bruce Anchor, Delmar Vryhof, InterMoor, MacGregor, NOV and Vicinay.

Key facts

There are four major mooring system options for a semi-submersible structure, shown in Figure 25 which provide compliance in different ways. The optimum design for each site is a technical and economic trade-off.

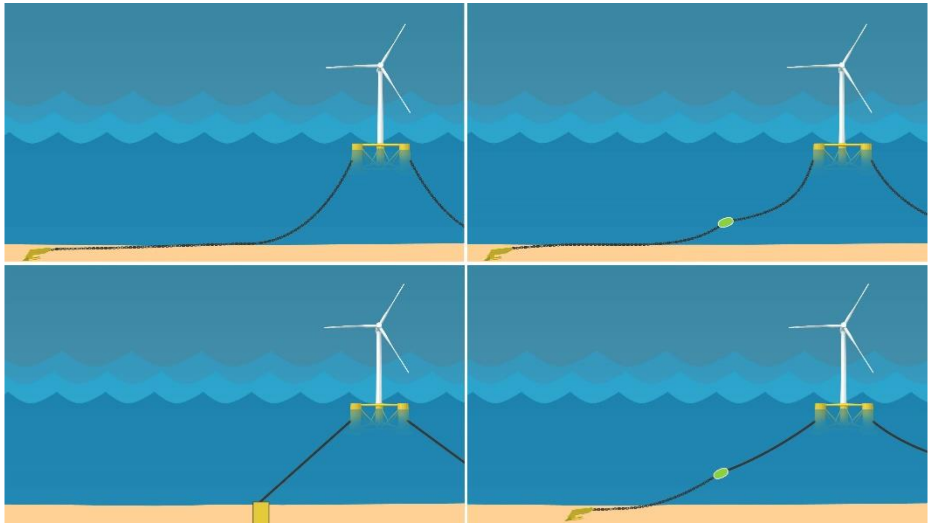

Figure 25 High-level mooring system options: plain catenary, multi-catenary, buoyant semi-taut and taut*, clockwise from top left. Image courtesy of BVG Associates. All rights reserved.*

- Plain catenary: A system that uses free hanging chain mooring lines, whose self-weight leads to the catenary shape. These connect the substructure to the anchors. A length of ground chain means that the anchors are loaded almost horizontally and, where ground conditions allow, use drag embedment anchors. It is the simplest mooring system design, with the least expensive anchor type, and is used at shallower sites. The radius from turbine to anchor is approximately six to eight times the water depth.
- Multi-catenary: A system that uses chain mooring lines and may include rope sections. Compliance is provided first by the catenary chain sections and by the elasticity of the rope section, where used. The compliance properties can be tuned by the addition of clump weights and floats. Where ground conditions allow, it is expected to be used with drag embedment anchors.

- Buoyant semi-taut: A system that uses a combination of chain at the top and bottom with a rope mid-section on each line. The ground chain ensures that the loads seen by the anchors are predominantly horizontal and buoyancy modules lift the rope sectors above the sea bed to prevent damage. Compliance is provided predominantly by the elasticity of the rope section.
- Taut: A system that uses rope lines connected under tension between substructure and anchors. Short sections of chain may be used at the top and bottom to make connections and adjust tension. Compliance is achieved through the properties of the rope section and from a load reduction device, if used. This option sees higher loads including high vertical loads on the anchors and so piled or suction anchors of greater capacity are needed. It has a smaller footprint than other mooring systems with a radius from turbine to anchor of approximately two times the water depth.

Mooring solutions for floating offshore wind turbines have been developed from technology proven for floating oil and gas platforms. They differ as, generally, floating offshore wind turbines are located in shallower water, have a different set of loads, and have lower consequences of failure as there is no oil spillage risk.

Mooring lines connect to a substructure at an angle to the vertical. The horizontal component of tension keeps the substructure on station and the vertical component of tension provides a restoring force that contributes to the stability of the substructure and turbine.

Most early mooring systems have been designed to be compliant and so reduce the extreme loads. Compliance can be achieved in several different ways:

- A catenary shape straightens out and lengthens under increasing load, according to its mass.
- The length of ground chain progressively lifts with increasing load, according to its mass.
- A taut or semi-taut mooring line provides some compliance, depending on its length and material properties.
- In-line dampers and other load reducing devices are being developed for use with taut and semi-taut moorings, which are typically located in the upper section of the line.

Mooring system designs can also be “restrained”, which means that they minimise motions.

A typical design value for excursion is 30 to 35% of the water depth. This means that the substructure could move up to 30 to 35 m away from its station, for a water depth of 100 m, and systems such as the dynamic array cables have to cope with this movement.

A three-line mooring system has been the preferred design on early demonstration projects.

Redundancy is a commonly used term, but one which can be misunderstood in the context of mooring system design – it does not mean that no failures will occur. The relevant standards for floating offshore wind turbine moorings provide guidance. It is up to engineers to either design by following the guidance or to persuade insurers that their novel mooring system designs are fit for purpose, which in turn will give confidence to investors and lenders.

The minimum cost of a mooring system is seen at depths of about 100 to 150 m. At shallower depths, the cost increases as complexities to do with relative wave height to water depth increase and substructure compliance is harder to manage. At greater depths, the cost increases because the lengths of mooring line are greater.

The mooring system restricts certain types of activity within the wind farm, such as fishing, depending on its detailed design.

BVGAssociates

The mooring system design must allow for ease of installation and hook-up, and ease of disconnection to allow for any major repair events.

What's in it

- B.3.1 Anchors
- B.3.2 Mooring lines
- B.3.3 Jewellery
- B.3.4 Topside connections

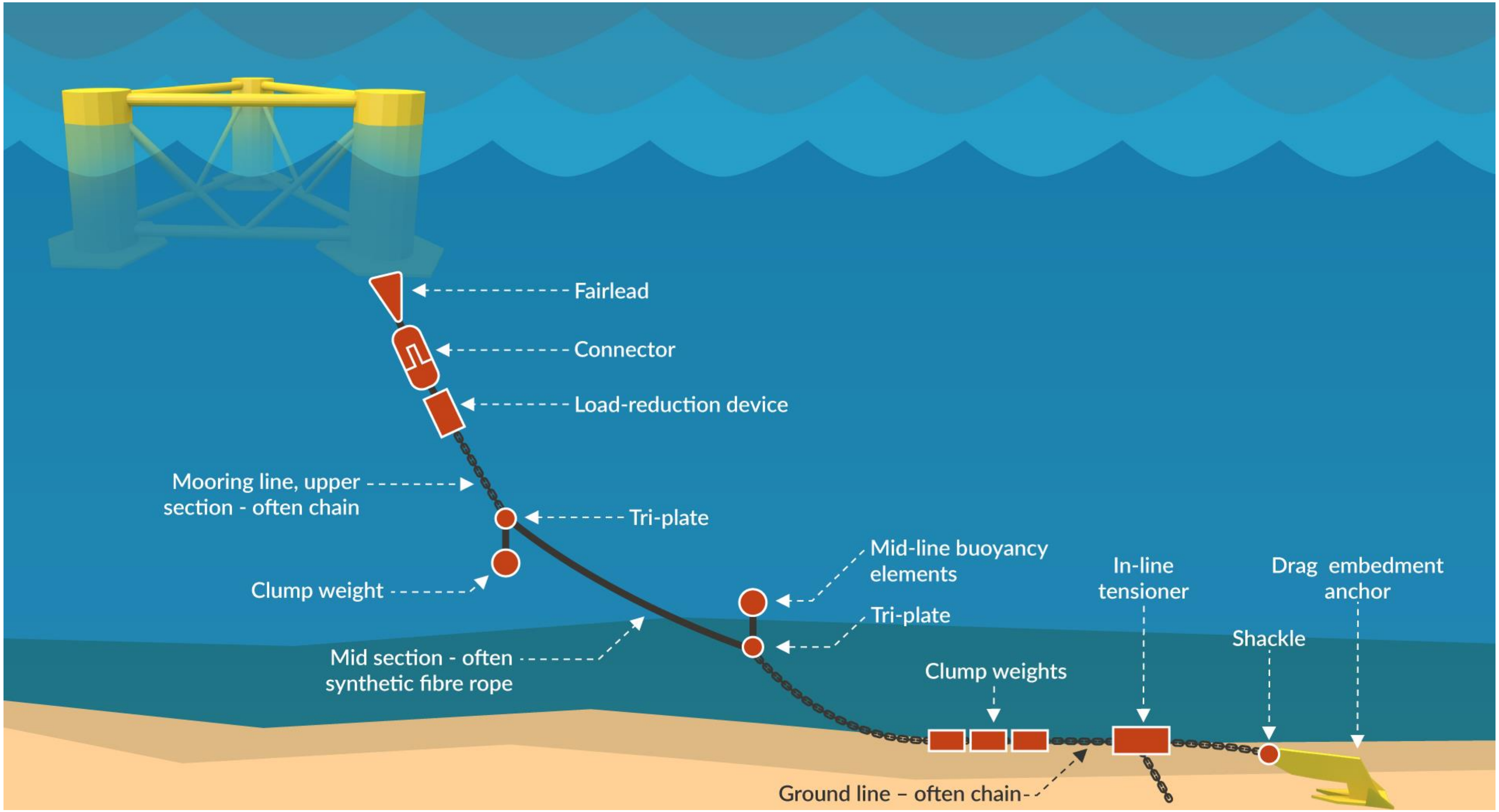

Figure 26 Typical mooring system components for floating offshore wind turbines. ***An actual system would not use all of these at the same time. Image courtesy of BVG Associates. All rights reserved.***

B.3.1 Anchors

Function

The anchors of a mooring system provide fixed points in the sea bed which can resist the loads from the mooring lines for the lifetime of the project. The reference configuration includes three anchors, one for each mooring line.

Figure 27 Suction pile anchor, drag embedment anchor and driven pile anchor. ***Images courtesy of Acteon, Principle Power and Acteon. All rights reserved.***

What it costs

About £17 million for a 450 MW floating offshore wind farm using drag embedment anchors.

Difficult ground conditions require the use of piled or suction anchors which could result in anchor costs that are several times higher.

Vertical and multi-directional loading from other foundation types, or shared anchors also increase anchor costs.

Who supplies this

Bruce Anchor, Delmar Vryhof, Global Energy Group, RCAM Technologies, Subsea Micropiles and Swift Anchors.

Key facts

Anchors are used across many different industries and so the existing design types are well established, although new devices are coming on to the market at low technology readiness levels, providing the opportunity to anchor in a wide range of ground conditions. The anchor types expected to be used most for floating offshore wind turbines are:

- Drag embedment
- Driven pile, and
- Suction pile.

Table 2 Description of major types of anchors expected to be used by floating offshore wind turbines.

	Drag embedment	Driven pile	Suction pile
Where used	Best suited to cohesive sediments that are not too stiff to impede embedment. Used where possible as lowest cost.	Can be used in a wide range of conditions, including where there are boulders or hard ground.	Requires sea bed conditions that are firm enough to hold suction but not so hard that penetration is impeded
Loading	Uni-directional, horizontal only	Multi-directional, horizontal, and vertical	Multi-directional, horizontal, and vertical
Installation	Simple, requires pre-tensioning	Driving by vibro- or impact-hammer causes noise	Relatively simple process: self-weight starts embedment, followed by suction
Removal	Are designed to be recoverable	Difficult to remove	Removal is the reverse of installation

The choice of which type of anchor to use is driven primarily by the set of loads it will encounter and ground conditions.

Floating offshore wind introduces larger numbers of anchors per site than are used by other markets and so the total installed cost is a major consideration.

An array of floating turbines has the potential to share some anchors, which would reduce the overall cost, as has been demonstrated at Hywind Tampen where 11 turbines share 19 anchors. Shared anchors must be designed to resist loading from multiple directions, and the consequence of cascade effects resulting from single/multiple line failures needs to be addressed.

A drag embedment anchor for a 15 MW turbine has a typical mass of 35 to 50 t.

What's in it

- Fabricated steel plate
- Pipes and valves (for suction anchors)

B.3.2 Mooring lines

Function

The mooring lines connect and transfer loads from the substructure to the anchor system for station-keeping and stability. The reference configuration uses three mooring lines.

Figure 28 Mooring chains stored on the quayside of a port. ***Image courtesy of Acteon. All rights reserved.***

What it costs

About £50 million for a 450 MW floating offshore wind farm.

Who supplies this

Bexco, Bridon-Bekaert, Dynamica Ropes, Lankhorst and Vicinay.

Key facts

A mooring line is unlikely to be made of the same material and specification along its full length. It can be thought of as having three sections:

- The upper section, which attaches to the substructure, is subject to the splash zone and sees the greatest loads.
- The middle section, in the free hanging section, is not subject to the splash zone or thrash zone.
- The ground line, which normally rests on the sea bed and attaches to the anchor. It needs to be heavy and stand up to the abrasion from movement across the sea bed under heavy loads, known as the thrash zone.

Typical pre-tension loads in a catenary system are 200 to 300 t.

Steel chain considerations:

- Stud-link chain is stronger and heavier than stud-less chain and better at preventing knot formation. Stud-less chain is cheaper for a given load and is less sensitive to fatigue loading.
- Steel chain specifications, for example, R2, R3, R4 and R5, determine the strength and material properties, although higher ultimate strength material will not necessarily have higher fatigue strength.
- Chain needs to be larger in the upper section, which sees the greatest loads. In addition, the link in a chain stopper receives higher loads than the rest of the chain.

- Steel chain is manufactured to several standard sizes, defined by the diameter of the steel rod it is made from, according to its loading and to enable compatibility with other mooring system components.
- Steel chain has considerable size and mass for the 185 to 220 mm diameter chains expected to be used for floating offshore wind turbines. For example, a single link of a 220 mm diameter chain has a mass of 700 kg and is over a metre long.
- Steel chain's high mass limits its use to shallower sites, generally less than 200 m deep.

Synthetic fibre rope considerations:

- Nylon has a long history of use in mooring systems. It is the most compliant synthetic mooring material, which could help to limit loads at shallow sites but would lead to larger excursions. There are concerns about its ability to accommodate fatigue loads and recent advances are focused on extending its lifetime.
- Polyester is expected to be used most often in the near term as it is more proven for permanent moorings than high modulus polyethylene (HMPE) and nylon. Polyester has a moderate level of compliance.
- HMPE is stiffer than polyester and offers high load capacity. It is ideally suited to taut mooring designs.
- Spliced eyelets are made at the end of each section of synthetic fibre rope, and steel eyelets are introduced. This is a high-skill process which allows connection using shackles or H-links to adjacent mooring components.
- A high-density polyethylene or polyurethane jacket is used to provide resistance from abrasion, in conjunction with a sand barrier to prevent abrasive sand particles from entering the body of the rope.
- A typical synthetic rope mooring line made from nylon, polyester or HMPE is significantly lighter, per metre, than a steel chain line for the same load.

Wire rope considerations:

- Wire ropes are lighter than chains with the same breaking load, have higher elasticity than chain and are easier to handle. The higher strength to weight ratio makes wire rope a potential alternative for deep water mooring systems. However, the drawbacks are its lower stiffness in the water column caused by its low weight and structural degradation when laid onto the sea bed without additional protection.
- A high-density polyethylene or polyurethane jacket is normally used to provide corrosion protection and some resistance from damage.

What's in it

- Drums, on which mooring lines are supplied
- Steel chain, either studded or stud-less
- Steel rope, spiral wound
- Synthetic fibre, including polyester, nylon and HMPE

B.3.3 Jewellery

Function

Jewellery is the term used to describe a range of items that are attached to mooring lines either to connect sections of a line or items that may be connected along the length of the line.

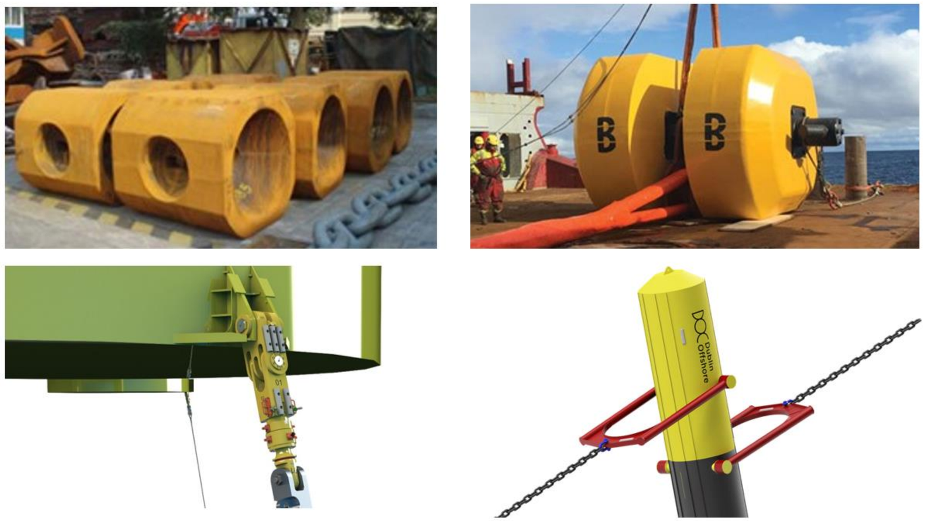

Figure 29 Clump weights, buoyancy elements, load reduction device, and floating substructure and mooring line connector *(clockwise from top left). Images courtesy of Hi-Sea Marine, Balmoral, Dublin Offshore and First Marine Solutions. All rights reserved.*

What it costs

About £8.6 million for a 450 MW floating offshore wind farm.

Who supplies this

- Connectors: Hydrosphere, InterMoor, and The Crosby Group.
- Clump weights: FMGC, Hydrosphere and InterMoor.
- In-line tensioners: Delmar Vryhof, Macgregor, and Flintstone Technology.
- Load reduction devices: Dublin Offshore, Intelligent Mooring, Tfl Marine.
- Mid-line buoyancy elements: Balmoral, DeepWater Buoyancy, InterMoor and SBT Energy.

Key facts

The major items include:

- Clump weights: these are masses, which can be several tonnes each, and are attached to mooring lines to tune the compliant response. They could be fitted to the mid or upper-section to resist substructure uplift, to the mid-section to form a multi-catenary shape or be added to the ground-section to convert vertical forces into horizontal forces at the anchor.
- H-links: used to join two sections of the mooring line together. This could be between dissimilar materials or the same material of a different size.
- In-line tensioners: this is a simpler alternative to a powered winch to adjust the tension in a mooring system which would sit on the sea bed for the life of the project. For example, Delmar Vryhof's Stevadjuster is positioned in the mooring line close to one of the anchors and is adjusted using a vertical pull from a bollard. A complete three-line mooring system can be tensioned using a single tensioner on one leg.
- Load reduction devices (LRDs): components within the load path that modify the mooring stiffness response to reduce mooring dynamic loads. By delivering engineered compliance, LRDs allow the mooring to be optimised for both cost and risk. LRDs come in a variety of forms including:

  - Gravitational devices using weight and buoyancy (such as the Dublin Offshore LRD)
  - Elastomeric devices using high-strain tensile materials (such as TFI Marine's SeaSpring)
  - Compressive devices using high-strain materials
  - Compressive devices using hydraulic systems.
- Mid-line buoyancy elements: these are flotation devices, which can provide several tonnes of uplift each, and are attached to mooring lines. Their function is either to lift the lower section of the mooring line above the sea bed to prevent damage or to fine tune the compliant response by forming a multi-catenary shape.
- Shackles: used to attach each end of the mooring line to the anchor and substructure, respectively.
- Swivels: used to stop twist in the mooring line.
- Tri-plates: flat plates with three holes, used to allow connection of two sections of mooring line with a clump weight or buoyancy element.

Most of these items are expected to be catalogue items used in other marine industries, initially, but could become more specialised to floating offshore wind's needs over time, particularly for volume and cost reduction.

What's in it

- Clump weights (made from cast iron)
- In-line tensioners (made from fabricated steel with some forged components)
- Load reduction devices (expected to be made from steel fabrications, glass fibre components, synthetic materials and/or hydraulic elements, depending on the type and specific design)
- Mid-line buoyancy elements (made from synthetic materials)
- Shackles, H-links, and swivels (made from forged steel)

B.3.4 Topside connections

Function

The topside connection connects the upper section of the mooring line to the floating substructure.

What it costs

About £3 million for a 450 MW floating offshore wind farm.

Who supplies this

First Subsea, Hydrosphere, InterMoor, Macgregor and The Crosby Group.

Key facts

The major items may include:

- A chain stopper which stops the chain and which is normally be used with a fairlead, which provides a “fair”, or good, “lead-in” for the anchor chain onto the substructure which helps reduce chafe and damage during connection and disconnection.
- A pull-through connector that fits around a chain and can be readily made and unmade. An example is Macgregor’s pull-through connector.
- A ball and taper connection that is easy to make and unmake. An example is First Subsea’s Ballgrab® connector.
- A fixed padeye is the simplest type of topside connection. It is a plate welded to the floating substructure with a hole, or “eye”, through which a shackle can be fitted.

The topside connector must either allow for the continuous dynamic motion of the floating substructure for a safe lifetime of at least 30 years or be subject to planned replacement.

The topside connection sees greater loads than any other part of the mooring line as it carries the weight of the mooring line and jewellery in addition to the dynamic loads from the substructure.

The detailed design of the topside connector is vital to ensure that it does not introduce stress concentrations that could add to the fatigue loading of the chain that is expected to be used in the upper section of the mooring line.

The topside connector must allow the connection and disconnection of the mooring lines.

Winches have been used on early demonstration projects, but they are not expected to be used on commercial-scale projects.

What’s in it

- Chain stoppers
- Connectors
- Padeyes
- Steel plate

B.4 Offshore substation

Function

The offshore substation connects the array cable system to the export cables. It contains a step-up transformer and power factor compensation equipment to reduce losses. For longer export cables the substation may also convert the power from alternating current (AC) to direct current (DC) to minimise losses further. It also provides switchgear to protect the grid from the wind farm, and vice versa, for fault conditions.

Figure 30 One of the fixed offshore substations used at the Hornsea One project. ***Image courtesy of Ørsted. All rights reserved.***

What it costs

About £67 million for a 450 MW floating offshore wind farm, considering an HVAC system.

Who supplies this

See details of individual components and systems below.

Key facts

A fixed offshore substation is the scenario described in this Guide, as dynamic export cable is not expected to be sufficiently proven for a project reaching FID in 2025. This will need to be in water depth of up to 100 m.

Offshore substations consist of a main electrical power system, auxiliary systems, a topside structure to house the systems, and a foundation. Offshore substations are often delivered as one element of a contract to connect the wind farm generating assets to the onshore transmission grid.

An HVAC substation topside (everything above the substructure) weighs between 1,200 and 3,000 t. A 450 MW wind farm is likely to have one offshore substation. Single HVAC substations of up to approximately 700 MW have been used.

An HVDC substation topside weighs between 12,000 and 18,000 t. A 1 GW wind farm would only have one HVDC offshore substation but could be connected to the turbines by several AC convertor stations which would transform the 66 kV output from the turbines up to 132 kV or higher to feed the HVDC substation. It is unlikely to be commercially attractive to use an HVDC connection for a single 450 MW wind farm that is 60 km from shore.

A developer typically works closely with its chosen HV engineer after the turbine has been chosen to optimise the export system as a key opportunity to reduce the cost of energy. By reducing the number of circuits, the substations need less switchgear and fewer transformers. This provides an opportunity to dispense with a substation or to reduce topside and foundation costs.

Standardisation of offshore substation design offers the potential to lower costs, although few developers have the project pipelines to justify the upfront costs.

With 66 kV subsea cables, near-shore wind farms up to 300 MW can be built without an offshore substation.

A typical HVAC platform is about 25 m above the sea and has an area of 800 m².

Although many offshore substations are not being used primarily as service platforms, they will still have a modestly equipped workshop and frequently a helideck.

In the UK, the offshore substation is ultimately owned and operated by a transmission operator (OFTO), although the wind farm owner has access and responsibility for the array cable entry and wind farm switchgear.

Floating offshore wind projects connected to offshore oil and gas facilities may not need an offshore substation, for example, Hywind Tampen.

What's in it

- B.4.1 HVAC electrical system
- B.4.2 HVDC electrical system
- B.4.3 Auxiliary systems
- B.4.4 Topside structure
- B.4.5 Foundation

B.4.1 HVAC electrical system

Function

An HVAC system converts and transmits the electrical power generated by the wind turbines, at say 66 kV, to the onshore substation through the export cables at say 220 kV.

What it costs

About £20 million for a 450 MW floating offshore wind farm.

Who supplies this

GE Grid Solutions, Hitachi Energy and Siemens Energy.

Key facts

Key components of an HVAC system include:

- HV switchgear sets to isolate and protect each array and export connection to the substation
- Transformers to transform to a higher voltage for onward transmission. A typical offshore substation has two or more transformers to improve availability. Transformers are oil cooled, requiring the use of fire and blast protection
- Passive and active reactive power compensation, typically large coils and power electronics, to improve the stability of the local grid system
- Earthing systems including lightning protection connecting electrical components and the substation structure
- Cable trays, tracks, clamps and supports to protect electrical items.

An HVAC transmission system, including the export cables and offshore and onshore substation, typically offers a lower lifetime cost (when also taking into account electrical losses) than the equivalent HVDC system for wind farms where the distance to the onshore substation is less than about 80 to 100 km. The factors used in choosing between HVAC and HVDC, however, are complex.

Technology is being developed to allow AC transmission to be used over longer distances, such as lower frequency AC transmission. Some wind farms have used additional reactive power compensation equipment, located on offshore platforms part way along the offshore cable route, or in onshore substations close to the coast.

HVAC electrical systems use standard technology and systems, which may be customised for use in a marine environment.

What's in it

- Auxiliary electrical, control and monitoring systems
- Cable trays, tracks, clamps, and supports to protect electrical items
- Earthing systems
- HVAC switchgear
- Industrial waterproof enclosures
- Passive and active reactive power compensation
- Transformers

B.4.2 HVDC electrical system

Function

An HVDC system converts and transmits the electrical power generated by the wind turbines, at 66 kV AC, and transformed to say 132 kV AC by AC convertor stations, to the onshore substation through the export cables at say 320 kV DC. Equipment in the onshore substation converts the voltage back to say 400 kV AC for connection to the onshore transmission grid.

Who supplies this

GE Grid Solutions, Hitachi Energy and Siemens Energy.

Key facts

Key components of an HVDC system include:

- HV switchgear sets to isolate and protect each array and export connection to the substation
- Converters to convert AC to DC at a higher voltage for onward transmission
- Earthing systems including lightning protection connecting electrical components and the substation structure, and
- Cable trays, tracks, clamps, and supports to protect electrical items.

An HVDC transmission system, including the export cables and offshore and onshore substations, typically offers a lower lifetime cost (when also taking into account the lower electrical losses of an HVDC system over these distances) than the equivalent HVAC system for wind farms where the distance to the onshore substation is greater than about 80 to 100 km. The factors used in choosing between HVAC and HVDC are, however, complex.

HVDC systems use relatively new technology and systems that are custom designed for the transmission of high power, say over 750 MW, over long distances. HVDC systems currently only operate point-to-point and require the use of a matched pair of converters at each substation (one onshore and one offshore).

Cost reductions have been seen in recent years and are expected to continue, driven by new technology and the increase in the use of interconnectors, as well as by offshore wind.

What's in it

- Auxiliary electrical, control and monitoring systems
- Cable trays, tracks, clamps, and supports to protect electrical items
- Converters
- Earthing systems
- HVAC and HVDC switchgear
- Industrial waterproof enclosures

B.4.3 Auxiliary systems

Function

Auxiliary systems are facilities that support the operation and maintenance of the substation and enable some wider wind farm maintenance activities.

What it costs

About £3.4 million for a 450 MW floating offshore wind farm.

Who supplies this

Communications and networks: Atos, Cisco and Semco Maritime.

Cranes: Demag, Granada and Kenz Figee.

Diesel generators: Aggreko, Caterpillar and Energyst.

Fire and blast protection: InterDam and Mech-Tools .

Heating, ventilation and air conditioning: Halton, Heinen & Hopman and Johnson Controls.

Helicopter fuelling systems: Imenco, Swire Energy Services.

Key facts

Like any other complex industrial facility, this offshore building needs fire detection and suppression systems along with security, safety, communications, and other monitoring systems.

Fire and blast protection is required because the transformers contain oil and coolants and present a fire risk. They need to be protected from fires elsewhere on the platform.

A standby generator is required to provide auxiliary power and lighting in the event of loss of connection to the onshore substation and to provide power to restart and reconnect to the onshore substation.

Also required are a control room, health and welfare and refuge for visiting crews, clean and black water systems, fuel tanks, LV power supplies, navigational aids, and safety systems.

What's in it

- Auxiliary electrical systems
- Clean and black water systems (normally for HVDC substations)
- Communication systems
- Control room & refuge
- Crane
- Fire and blast protection systems
- Fuel tanks (normally for HVDC substations)
- Heating, ventilation, and air conditioning equipment
- Monitoring systems
- Standby generator (normally for HVDC substations)

B.4.4 Topside structure

Function

The topside structure provides support and protection for the electrical and auxiliary systems.

What it costs

About £32 million for a 450 MW floating offshore wind farm.

Who supplies this

Helideck: Aluminium Offshore and Bayards.

Structure: Babcock, Bladt, Chantiers De l'Atlantique, Heerema, Hollandia, HSM Offshore, Sembcorp Marine and Smulders.

Key facts

The topside is a complex steel structure, incorporating many safety considerations and services.

A helideck is generally specified to enable helicopter landing (see O.4.4 for further information). Offshore helidecks are generally aluminium to minimise corrosion and weight. An accident during take-off or landing can result in hundreds of litres of jet-fuel spilling from ruptured fuel tanks so stringent safety regulations are in place with the requirement for an integrated fire-fighting system. The use of helicopters for crew transfer is an integral part of maintenance and service operations for some but may only be used for emergency access or egress by others.

What's in it

- Helideck
- Heliwinch

- Steel structure

B.4.5 Foundation

Function

The offshore substation foundation supports the topside structure.

Figure 31 Offshore substation jackets. ***Image courtesy of Ørsted. All rights reserved.***

What it costs

About £12 million for a 450 MW floating offshore wind farm, using a jacket foundation for an HVAC offshore substation.

Who supplies this

Bladt, Chantiers De l'Atlantique, Hollandia, HSM Offshore, Lamprell, Navantia, Sembcorp Marine and Smulders.

Key facts

Offshore substations can either be supported by fixed foundations or floating substructures. Fixed offshore substation foundations are likely to be jackets. These are steel lattice structures with usually three or four legs that are anchored to the sea bed using pin piles or suction buckets. Floating offshore substations can use any of the same substructure types available to support turbines, that is barge, semi-submersible, spar, or TLP (see B.2 for further information).

Floating offshore substations are yet to be commercially proven. For this reason, we expect early floating offshore wind farms to use offshore substations with fixed jacket foundations. We expect floating offshore substations to be adopted once the technology is proven.

What's in it

- Pin piles or suction buckets
- Secondary steel
- Steel jacket

B.5 Onshore substation

Function

The onshore substation transforms power to grid voltage, for example up to 400 kV. Where a HVDC export cable is used, the substation converts the power to three-phase AC. It also provides switchgear to protect the grid from the wind farm, and vice versa, for fault conditions.

Figure 32 Onshore substation. *Image courtesy of ScottishPower Renewables. All rights reserved.*

What it costs

About £37 million for a 450 MW floating offshore wind farm.

Who supplies this

They are generally contracted to the same main contractor as the B4 Offshore substation.

Key facts

There are no fundamental differences between onshore substations for fixed or floating offshore wind farms.

The onshore substation is often the first part of the wind farm to be built, about a year before offshore construction. In some cases, work may start ahead of FID for the wind farm to mitigate the risk of stranded generation assets.

Typically, they are two parts to the substation: the wind farm side owned by the offshore transmission owner (OFTO in the UK) and the grid side owned by the relevant grid operator (National Grid Electricity Transmission in England and Wales, SSE Networks or SP Energy Networks in Scotland, or Northern Ireland Electricity Networks).

The wind farm side of the substation is larger, consisting of the majority of the electrical system and a building with a control room, office and storage. The grid side of the substation may be an extension to an existing facility or a new one if this is not practical.

Many of the electrical components are similar in specification to the offshore substation, but constraints on weight and space are not as critical. The substation will contain metering equipment to measure electricity exported to the grid.

The onshore substation is ideally located close to the offshore export cable landfall to limit the length of the onshore cable route, but it may be up to 60 km from landfall.

The area of the onshore substation is likely to be about 5 ha for an HVAC system and 7.5 ha for an HVDC system.

The onshore substation is likely to be contracted to a supplier of transmission systems with a substantial amount of the work contracted to a civil engineering contractor.

What's in it

- B.5.2 Buildings, access, and security
- B.5.1 Electrical system

B.5.1 Electrical system

Function

The onshore substation electrical system converts the power generated from the wind farm into a form that can be integrated into the wider transmission network.

What it costs

About £26 million for a 450 MW floating offshore wind farm, considering an HVAC system.

Who supplies this

GE Grid Solutions, Hitachi Energy and Siemens Energy.

Key facts

The onshore substation has the same types of electrical system components as the offshore substation. This typically includes switchgear, transformers (if HVAC), converters (if HVDC), reactive power compensation and earthing systems.

What's in it

- B.4.1 HVAC electrical system
- B.4.2 HVDC electrical system

B.5.2 Buildings, access, and security

Function

Buildings, access, and security provide physical protection and security for the onshore electrical equipment that connects the wind farm to the onshore transmission network.

What it costs

About £11 million for a 450 MW floating offshore wind farm.

Who supplies this

The buildings, access, and security can be contracted to any suppliers with suitable track records of supplying to similar types of civil engineering projects.

Key facts

The buildings and associated compounds are custom designed to suit the specific technical and planning requirements of the project.

For an HVAC substation, indoor space is required for housing some of the switchgear, monitoring systems, and associated LV systems and welfare facilities for visiting technicians. Often about the same area of outdoor space is required for compounds for outdoor HV switchgear, termination of HV overhead lines, storage, and car parking.

For an HVDC substation, indoor space, typically at least two storeys high, houses the HVDC converter, monitoring systems, and associated LV systems and welfare facilities for visiting technicians. Outdoor space is also needed for compounds for outdoor HV switchgear, termination of HV overhead lines, storage, and car parking.

What's in it

- Auxiliary and LV systems

- Monitoring systems
- Welfare facility

I Installation and commissioning

Function

Includes all installation and commissioning of turbines, offshore balance of plant and onshore balance of plant. This starts with the shipping of major items to the construction port and ends when the fully commissioned assets are handed over to operational teams.

What it costs

About £170 million for a 450 MW floating offshore wind farm. This includes the installation of the turbines and balance of plant, with related offshore logistics. It also includes developer's insurance, construction project management and spent contingency (not itemised in sections below).

Who supplies this

Companies capable of engineer, procure, construct and installation services (EPCI) for significant installation scopes are expected to include Boskalis, Heerema, Maersk, Saipem, Subsea 7, TechnipFMC and Van Oord.

Installation contractors for smaller scopes are listed in relevant sections.

Key facts

The typical installation process is as follows, noting there are parallel operations where possible:

1. Offshore substation installation
2. Offshore cable installation
3. Onshore export cable installation
4. Anchor and mooring pre-installation
5. Floating offshore wind turbine assembly, and
6. Floating offshore wind turbine installation.

The installation period for a 450 MW floating offshore wind farm is typically three years from the start of onshore works.

Weather downtime is a key cost consideration for any offshore activity with a third of time often lost through waiting on weather.

Significant wave height (Hs) is the most widely used measure of limitation for offshore activity. In practice this needs to be combined with wave periodicity, direction, persistence (the length and frequency of suitable weather windows), wind speed, wind direction and tidal flow to determine workability for different activities.

Sites farther from shore are typically associated with more adverse weather conditions and higher weather downtime.

Weather windows of sufficient duration are required for tow-out and hook-up to moorings and array cable. Hook-up operations at site such as cable pull-in require more benign conditions compared to fixed wind farms, however offshore lifts are avoided as final assembly of the turbine with the floating substructure is completed in port.

The opportunity for innovation to reduce costs is substantial. Decreasing offshore cycle times and increasing the operating range of offshore operations is key as this increases vessel utilisation and accelerates project delivery. Addressing health and safety considerations also needs to remain a focus, as new innovations specific to floating offshore wind are introduced.

Installation services are supplied on a day rate or lump sum basis, principally for the vessel or vessels and the crew and equipment onboard. Additional costs are fuel and harbour dues.

For floating projects, developers may opt for a single foundation and balance of plant installation contract, because of the multiple potential interface risks and that installation processes need to be engineered around the floating substructure design.

What's in it

- I.1 Offshore substation installation
- I.2 Offshore cable installation
- I.3 Onshore export cable installation
- I.4 Anchor and mooring pre-installation
- I.5 Floating offshore wind turbine assembly
- I.6 Floating offshore wind turbine installation
- I.7 Inbound transport
- I.8 Construction port
- I.9 Offshore logistics

I.1 Offshore substation installation

Function

The installation of the offshore substation consists of the transfer of the substation from its quayside fabrication site and the installation on the foundation.

Figure 33 Topside structure of an offshore substation being lifted onto a jacket foundation. *Image courtesy of ScottishPower Renewables. All rights reserved.*

What it costs

About £11 million for a 450 MW floating offshore wind farm.

Who supplies this

Boskalis, DEME, Heerema, Saipem, Scaldis Salvage & Marine, Seaway 7, Van Oord and ZPMC.

Offshore substation installation often forms part of the substation supply contract.

Key facts

Fixed offshore substation installation is a heavy lift operation (minimum of 2,000 t) requiring vessels with sufficient crane capacity. Vessels with the necessary lift capacity often do not have the deck space to accommodate a substation platform. The substation is therefore floated out of the fabrication facility on a barge, usually directly to the wind farm site.

The substation foundation, which is installed prior to the topside structure, may be a monopile or a jacket.

The installation process for floating offshore substations will be similar to the process described for installing floating substructures for floating offshore wind turbines (see I.6 for further information).

What's in it

- I.1.1 Substation installation vessel

I.1.1 Substation installation vessel

Function

The substation installation vessel transports and lifts the offshore substation into position on a pre-installed foundation.

What it costs

This is included in the substation installation contract.

- Day rates for most substation installation vessels are about £230,000.
- Semi-submersible vessels may have day rates greater than £450,000 but if the oil and gas market is quiet then rates may be more competitive.

Who supplies this

Bonn & Mees, Heerema, Huisman, Saipem, Scaldis Salvage & Marine, Seajacks, Seaway 7 and ZPMC.

Key facts

There are four main types of substation installation vessel:

- Barge
- Heavy lift vessel
- Semi-submersible vessel, and
- Sheerleg crane vessel.

The choice of vessel is likely to be driven by market factors and, in many cases, if vessels serve other markets. As a result, there has been little investment in vessels for the offshore wind market specifically.

Heavy lift vessels used in offshore wind include Rambiz, Sleipnir, Stanislav Yudin and Samson.

Crane ratings required for substation installation vessels are from 900 t to over 3,000 t.

What's in it

- Auxiliary cranes
- Crane
- Dynamic positioning system
- Gangway
- Helideck
- Propulsion systems

I.2 Offshore cable installation

Function

The installation of the offshore array and export cables allows the power transfer from each turbine to the onshore export cables.

What it costs

About £63 million for a 450 MW floating offshore wind farm. This includes the cable-laying vessel (CLV), cable lay and burial, cable pull-in and electrical testing and termination. It also includes survey works, route clearance and the installation of cable protection systems.

Who supplies this

Marine contractors: Boskalis, DEME, DeepOcean, Global Marine, Global Offshore, Huisman, Jan de Nul, Oceanteam, Seaway 7 and Van Oord.

Cable manufacturers with installation capabilities: Nexans, NKT and Prysmian.

Key facts

All offshore cable installation activities are preceded with a survey to define the route and identify any unexploded ordnance (UXO). This is followed by a pre-lay grapnel run (or alternative method) to clear debris from the cable route.

Offshore cable installation involves cable laying, and in some cases cable burial and trenching. This typically involves one or two runs depending on the ground conditions, the equipment available and the preferences of the developer and contractor.

Test and inspection typically include independent observation of all cable handing and laying operations, often with subsea video recording.

To avoid unnecessary handling, it is preferred that subsea cables are loaded directly onto an installation vessel from the factory. Lengths may be pre-cut.

Cable protection typically falls within the installer's scope of work (see B.1.3.2 for further information). Other techniques like rock dumping and mattresses are also used to ensure burial and protection on cable crossings.

What's in it

- I.2.1 Export cable installation
- I.2.2 Array cable installation
- I.2.3 Cable-laying vessel
- I.2.4 Cable-laying equipment
- I.2.5 Cable pull-in
- I.2.6 Electrical testing and termination

I.2.1 Export cable installation

Function

The installation of export cables enables the connection between the offshore substation and the onshore export cable.

The site definition assumes the use of a fixed substation, so the export cable installation processes described in this section is the same as that for a fixed offshore wind farm.

Figure 34 **Offshore array cables installed at landfall. Image courtesy of Jan de Nul. All rights reserved.**

What it costs

About £20 million for a 450 MW floating offshore wind farm. This includes the CLV, and cable lay and burial. It also includes survey works, route clearance and the installation of cable protection systems.

Who supplies this

Marine contractors: Boskalis, DEME, DeepOcean, Global Marine, Global Offshore, Huisman, Jan de Nul, Oceanteam, Seaway 7 and Van Oord.

Cable manufacturers with installation capabilities: Nexans, NKT and Prysmian.

Key facts

Export cable installation starts with the shore pull-in (first-end pull-in) (see B.1.2 for further information). The CLV then moves off, laying the cable as it goes.

Export cables are laid in sections which are as long as possible to avoid expensive subsea joints.

Export cables are typically buried 1 to 4 m below the sea bed. Burial usually takes place simultaneously as the cable is laid using a cable plough, as immediate burial and protection is obtained in a single pass which reduces costs. A two-stage process may also be used where the cable is first laid on the sea bed, after which a vessel with a trenching remotely operated vehicle (ROV), and a vertical injector and jetting sled, undertakes the burial. The approach taken depends on a number of factors including the availability of equipment, cost and ground conditions.

At the offshore substation, the cable is either set down and wet-stored for subsequent pull-in to the substation, or immediately pulled-in which is preferred. Electrical terminations are made after pull-in. Static export cables are used from shore up to the fixed offshore substation and pulled-in through J-tubes.

Floating substructures may be used in the future to support offshore substations and will require dynamic lengths of export cable. These will be installed in a similar way to dynamic array cables.

Most export cable manufacturers have CLVs and install export cables themselves.

What's in it

- B.1.3 Cable accessories
- I.2.3 Cable-laying vessel
- I.2.4 Cable-laying equipment
- I.2.5 Cable pull-in
- I.2.6 Electrical testing and termination
- B.1.2 Export cable
- O.2.2.2.1 Remotely operated vehicle

I.2.2 Array cable installation

Function

The installation of array cables enables the connection of the installed floating offshore wind turbines to the offshore substation.

What it costs

About £34 million for a 450 MW floating offshore wind farm. This includes the CLV, and cable lay and burial. It also includes survey works, route clearance and the installation of cable protection systems.

Who supplies this

Marine contractors: Boskalis, DEME, DeepOcean, Global Marine, Global Offshore, Huisman, Jan de Nul, Oceanteam, Seaway 7 and Van Oord.

Cable manufacturers with installation capabilities: Nexans, NKT and Prysmian.

Key facts

Array cables can either be installed after the floating offshore wind turbine has been installed or can be pre-installed. The advantage of pre-installation is that cable laying is removed from the installation's critical path. There are challenges to store the dynamic section with its jewellery on the sea bed and recovering it without damage, so it has not become established practice yet.

Array cable installation after the floating offshore wind turbine installation:

- This starts with the cable pull-in at the offshore substation, if it is the first connection in the array loop or string, otherwise it starts at a floating offshore wind turbine.
- Cable accessories such as bend stiffeners and buoyancy modules are attached to the cables on the CLV.
- The cable is then laid away using the CLV towards the next turbine. The buoyancy and ballast modules attached to the cable create the lazy wave shape for the dynamic cable section. After the cable touches down, it is either laid on the sea bed or buried using a cable plough or a trenching ROV.
- The cable is pulled-in at the next turbine to complete the single array length.

Array cable installation where array cables are pre-installed prior to floating offshore wind turbine installation:

- Pre-installing array cables allows as much work as possible to be completed ahead of the installation critical path, so that electrical connection of the floating offshore wind turbine can be completed faster.
- The array cables are installed using the method described above but the cable ends are laid on the sea bed for wet storage with a marker buoy attached.
- At the point of hook-up, each cable end is picked up using an ROV and handled by a support vessel. The support vessel attaches accessories, manages the cable pull-in and termination at the turbine or offshore substation.

Array cable installation with joints or connectors (see B.1.3.4 for further information):

- Some array cable designs use different cable for the static part on the sea bed, and for the dynamic part. If factory joints are used offshore connectors can be avoided and the installation process is almost unchanged from laying a continuous section of cable.
- Where designs use a connector between sections of static and dynamic array cable:
  - Dry mate connectors require the connection between static and dynamic cable sections to take place on the deck of a vessel.

- Wet mate connectors allow for connections to be completed underwater using ROVs.

Array cables are usually installed by marine contractors.

What's in it

- B.1.1 Array cable
- Buoyant junction boxes
- B.1.3 Cable accessories
- I.2.5 Cable pull-in
- I.2.3 Cable-laying vessel
- I.2.6 Electrical testing and termination
- I.2.4 Cable-laying equipment
- O.2.2.2.1 Remotely operated vehicle

I.2.3 Cable-laying vessel

Function

The cable-laying vessel (CLV) lays the cables between the floating offshore wind turbines and offshore substation, and between the offshore substation and the onshore transition joint pit at cable landfall.

Figure 35 Cable-laying vessel. *Image courtesy of Jan de Nul. All rights reserved.*

What it costs

This is included in the offshore cable installation contract.

A typical day rate for a CLV is about £150,000.

Who supplies this

Marine contractors: Boskalis, DEME, DeepOcean, Global Marine, Global Offshore, Jan de Nul, Oceanteam, Seaway 7 and Van Oord.

Cable manufacturers with installation capabilities: Nexans, NKT and Prysmian

Key facts

The same vessels may be used for export and array cable installation, although CLVs used to install export cables typically have larger carousels to accommodate longer cables. CLVs may need to have shallow drafts to install the export cables in shallow water close to shore.

Simultaneous lay and burial can be carried out with a variety of burial tools. In that case, the cable is buried during the lay to obtain immediate protection. Otherwise, a post-lay burial is required.

CLVs are characterised as follows:

- Up to 30 m (breadth) by 140 m (length) and can operate at a speed up to 14 kn (transit speed).
- Accommodation for a crew of up to 90.
- The current capacity of carousels is of up to 10,000 t. Some contractors offer vessels with a double carousel which can increase carrying capacity (for example Jan de Nul's Isaac Newton).
- Likely to be equipped with a 3D motion compensated crane with up to 25 t capacity and a 25 t A-frame.
- Generally equipped with a motion-compensated personnel transfer gangway and a helideck.

What's in it

- I.2.4 Cable-laying equipment
- Carousel
- Crane
- Personal transfer gangway
- O.2.2.2.1 Remotely operated vehicle

I.2.4 Cable-laying equipment

Function

The equipment ensures that the cable is safely deployed from the vessel to the sea bed.

What it costs

This is included in the offshore cable installation contract.

Who supplies this

Cable-laying equipment is usually provided by the cable installation contractor; in that case, it is either part of the vessel or must be mobilised.

Equipment manufacturers: Ecosse Subsea, Fraser Hydraulic Power, Hulst Cable Equipment, MacArtney, Osbit, Royal IHC, SMD and Sparrows.

Equipment rental providers: Caley Ocean Systems, CWind, Demanor, Drammen Yard, Ecosse Subsea and RentOcean.

Key facts

Cable handling equipment is designed to protect the cable's integrity and to ensure the cable is deployed in a controlled manner at the correct speed.

The cable is stored either on a carousel, in a static tank or on a reel. To exit the storage area, a tensioner is used to grip and move the cable toward the chute where the cable is deployed onto the sea bed whilst ensuring no bending takes place below the cable's minimum allowed bend radius.

During a second-end pull-in or pull-in at the offshore substation, a quadrant is used to deploy the end of the cable on the sea bed before it is pulled in.

What's in it

- Cable highway or rollers

- Chute
- Quadrant
- Tensioners

I.2.5 Cable pull-in

Function

For the array cable, the pull-in consists of the pulling of the cable into the offshore substation, floating offshore wind turbine or buoyant junction box.

For export cables, the pull-in consists of pulling the cable into the onshore transition joint pit as well as into the offshore substation.

What it costs

About £5 million for a 450 MW floating offshore wind farm.

Who supplies this

The cable pull-in is usually provided by the offshore cable installation contractor.

Key facts

The installation of the export cable starts with the onshore pull-in at the beach, during which the CLV is anchored offshore. A pull-in head is attached and the cable winched on floats or through a pre-laid duct to the onshore transition joint pit, where it is eventually jointed to the onshore cable. The CLV then moves off, laying the cable as it goes. Depending on the landfall site, some projects require horizontal directional drilling which may extend to the first short length of burial offshore. In other cases, the cable may be transferred to a third-party shallow draft barge or amphibious vehicle to bring the cable to shore.

At the offshore substation, it is preferred to pull-in the export cable to the substation immediately after it has been laid by the CLV. It may however be necessary to wet store the cable if, for example, the substation is not yet installed or if the CLV is not equipped to conduct the second-end pull-in at the substation. The offshore pull-in process is normally as follows:

- End-fitting and pull-in head is installed onto the cable end

- Bend stiffener is installed onto the end-fitting and the cable
- The cable is lowered into the sea
- A messenger wire that was placed in the I-tube/J-tube is attached to the pull-in head using an ROV
- Pull-in head is pulled into the I-tube/J-tube using a winch, and
- End fitting is connected to the hang-off at the substation or the floating substructure.

The post-lay array cable installation process, where the array cable is laid after the floating offshore wind turbine has been installed, starts with the pull-in at the substation using a similar process to that described above. Pull-in at the floating substructure is carried out in a similar way. In addition, buoyancy devices and bend stiffeners are attached to the dynamic part of the cable before it is deployed. Once the cable has been pulled-in the CLV then moves off to the next location, laying the cable as it goes and pulling it in once it arrives at the following location. For second-end pull-ins, a quadrant is generally used.

For pre-lay array cable installation, the cable laid to rest on the sea bed for pull-in once the floating offshore wind turbine has been towed to site.

New methods for pre-and post-lay array cable installation are expected that will allow faster cable installation in a wider range of metocean conditions, for example:

- Array cables can also be pulled-in, terminated and connected in a buoyant junction box or buoyant connector which is then connected to the floating offshore turbine. This solution allows for easier connection to, and disconnection from, the floating offshore wind turbine.

What's in it

- Barge
- Float
- Horizontal directional drilling
- Messenger wire
- Quadrant
- O.2.2.2.1 Remotely operated vehicle
- Winch

BVGAssociates

I.2.6 Electrical testing and termination

Function

Electrical testing is designed to test and prove cable integrity whilst termination enables a reliable connection to be made.

What it costs

About £4 million for a 450 MW floating offshore wind farm.

Who supplies this

Electrical testing and termination is usually provided by the offshore cable installation contractor.

Manufacturers of electrical testing equipment and termination tools: 360 Wind, Axess Group, Baur, JDR, Megger, Pfisterer, Tekmar, V&SH Offshore and WT Henley.

Key facts

Cables undergo a series of tests before dispatch from the manufacturer, dependent on the cable type and voltage class, including:

- Cable (and accessories) pre-qualification tests and type tests
- Cable (and accessories) type tests
- Cable routine electrical tests on each manufacturing length before jointing and armouring
- Sample tests
- Routine factory splice tests, and
- Tests on complete cable lengths including factory installed joints (if any).

Terminations are made after the cable has been pulled into the offshore substation or floating substructure. The armouring and insulation of the cables is stripped back and the cores are connected to a termination plug. The plug is then interfaced into a designated junction box or switchgear using a connector. A similar procedure is conducted for the fibre optic cable.

Terminating high-voltage cables is a highly skilled process that takes time to learn.

Prior to making terminations, a series of electrical tests are performed to prove the cable's electrical integrity. These include low frequency tests, insulation resistance tests, time-domain reflectometry tests and optical time-domain reflectometry.

After the cable is pulled into the transition joint pit on shore, it is terminated at the beach joint.

What's in it

- Cable trays
- Connection cables
- Hang-off clamp
- Power supply
- Test and diagnostics device
- Termination plug

I.3 Onshore export cable installation

Function

The installation of the onshore export cable completes the connection between the offshore export cable and the onshore substation.

Figure 36 Onshore export cable trenching process. *Image courtesy of Ørsted. All rights reserved.*

What it costs

About £3 million for a 450 MW floating offshore wind farm, depending on distance and complexity of route.

Who supplies this

Construction companies: Balfour Beatty, J Murphy and Sons, NKT and Nexans.

Marine contractors: DeepOcean and Global Offshore.

Key facts

The subsea cables terminate a short distance inland at the transition joint pit. This could be located on the beach, behind a sea defence, or up to 1 km inland.

Onshore cabling is generally underground to address local concerns over the siting of overhead power lines.

There are a range of local services used before and during the cable installation. These include wheel washing, road cleaning, traffic management, signage and temporary bridges over rivers and ditches.

At least one site compound is established along the cable route. These sites provide equipment storage, car parking and welfare facilities for staff. Typically, they are around 1 ha in size.

Before construction, site investigation and environmental work is undertaken to plan the installation and minimise impact on the surroundings.

A cable corridor is used during installation, which comprises the cable trench, storage for spools and access road.

Installation is carried out using open trenches, typically around 1 m wide and up to 1 km in length (depending on the cable) or by placing ducts into the trenches and covering them over more quickly. With ducting, it is typical to use medium density polyethylene (MDPE) ducts which are laid in the trench and the cable pulled through the ducts at a later time in up to 1 km lengths. This option allows excavation, duct installation and backfilling to be completed in sections of up to 120 m in a day. This minimises the amount of excavation left open outside working hours, which can help reduce environmental and safety concerns.

Where the cable crosses obstacles such as roads or railways, or encounters difficult or highly sensitive conditions, directional drilling may be used to route and pull the cable under the obstacle without the need for trenching.

Specialist drilling equipment creates a bore that passes the obstacle and can be up to 1 km in length. Drilling mud is used as lubrication, and this is recycled through a temporary mud lagoon during construction and disposed of after construction. Once drilled, a cable duct is then pulled through and the cable is then pulled through again using specialist equipment.

The cable is tested to ensure a complete circuit is in place. Once fully installed, an energised test is carried out to verify operation at or close to the intended voltage.

Care is taken to reduce the impact on endangered species such as newts, bats, and dormice, which might require specialist environmental monitoring and mitigation.

What's in it

- Drilling equipment
- Onshore cable-laying equipment
- Trenching equipment

I.4 Anchor and mooring pre-installation

Function

The pre-installation and testing of anchors and mooring lines at site. Completing as much pre-installation as possible ahead of the installation critical path allows the hook-up of the floating offshore wind turbine to be completed faster.

What it costs

About £31 million for a 450 MW floating offshore wind farm.

Who supplies this

Bourbon Offshore, Bridon-Bekaert, First Subsea, Kvaerner/DOF Subsea JV, Lankhorst, PSG Marine & Logistics, Strainstall, TechnipFMC and Tronds Marine AS.

Key facts

The pre-installation begins by installing an anchor on the sea bed. The process depends on the anchor type (see B.3.1 for further information):

- Drag embedment anchors are installed by placing the anchor on the sea bed and using the pulling force of the anchor-handling vessel (AHV) to obtain the necessary embedment which is normally between 1 and 2 m.
- Suction embedment anchors are installed by lowering a suction pile to the sea bed which self-penetrates part-way into the sea bed under its own weight. The piles are then embedded to their full depth by evacuating seawater from inside the pile using a pump on the anchor operated by a specialised ROV.
- A piled anchor is installed by lowering a pile to the sea bed which penetrates the sea bed under its own weight. A pile hammer is then used from the AHV

to obtain the required penetration depth. Piled anchors can also be drilled and grouted into place, depending on ground conditions.

Anchors are proof loaded for 15 to 30 minutes, according to the standard used, using the pulling force of the AHV to ensure sufficient holding capacity. The use of an in-line tensioning device to pull against a temporary reaction anchor, or an opposing anchor of the mooring system, substantially reduces the bollard pull required.

The lower section of the mooring line, often anchor chain, is connected to the anchor during installation:

- For drag embedment anchors it is attached before the anchor is embedded, as the attachment point is below the sea bed once it is embedded.
- For suction and piled anchors, it is attached after the anchor is installed.

If there is a section of synthetic fibre rope in the mooring line, this section would not be connected at this time.

A submersible marker buoy is connected to the end of the mooring line to support retrieval for later hook-up operations.

What's in it

- I.4.1 Anchor-handling vessel
- B.3.1 Anchors
- Marker buoys
- B.3.2 Mooring lines

I.4.1 Anchor-handling vessel

Function

AHVs are specialist vessels used for the pre-laying of anchors and mooring lines, and the tow-out and hook-up of floating offshore wind turbines.

Figure 37 Anchor-handling vessel. ***Image courtesy of Vryhof. All rights reserved.***

What it costs

This is included in the anchor and mooring installation contract.

The typical day rate for a 200 t bollard pull AHV is about £50,000. Smaller AHVs have a typical day rate of between £20,000 and £30,000.

Who supplies this

Boskalis, Bourbon Offshore, Damen, DOF Subsea, Maersk, MMA offshore, Siem Offshore, SEACOR Marine, Solstaad Offshore and Vard Marine.

Key facts

The same vessels may be used for anchor and mooring pre-installation, and tow-out operations.

AHVs have sufficient deck space to carry between four to six anchors per trip, depending on the design of the anchors. AHVs are classed by their dynamic positioning or station keeping abilities and bollard pull capacity.

Large AHVs are characterised as follows:

- Up to 25 m (breadth) by 95 m (length) and can operate at a speed up to 20 kn (transit speed)
- Accommodation for a crew of up to 60
- Maximum cargo capacity of 800 t
- Minimum bollard pull of 200 t, and
- Likely to be equipped with towing and anchor-handling winches, stern roller, knuckle boom cranes, towing and stopper pins.

For tow-out and hook-up operations the main towing AHV should have a bollard pull of 200 t. A vessel of similar bollard pull is required for installing drag embedment anchors. Two smaller AHVs usually support tow-out and hook-up operations. These vessels have a bollard pull capacity of between 50 to 100 t.

What's in it

- Anchor-handling cranes
- Anchor-handling winches
- Towing and stopping pins
- O.2.2.2.1 Remotely operated vehicle

I.4.2 Installation equipment

Function

Installation equipment used on board vessels and in the sea to pre-install anchors and mooring lines, and to tow-out and hook-up floating offshore wind turbines.

Figure 38 Stevtensioner and Stevadjuster. *Images courtesy of Vryhof. All rights reserved*.

What it costs

This is included in the anchor and mooring installation contract.

Who supplies this

CAPE Holland, DEME, Fistuca, Huisman, IQIP, Menck, PVE, NOV, Sumitomo and W3G Marine.

Key facts

An AHV is typically equipped with a stern roller, crane, and winches.

- Anchor-handling winches, and a stern roller are used to launch drag embedment anchors and mooring chains.
- Cranes are used to place suction and piled anchors on the sea bed. Pumps are used to evacuate water for suction anchors. Pile hammers, drill and grout spreads are used for piled anchors.
- Towing winches are used during tow-out of floating offshore wind turbines and have a holding load of approximately 600 t.

Further installation equipment carried depends on the operation.

- Winches and ROVs are used for retrieval of mooring lines during hook-up operations. ROVs are used to locate submerged marker buoys and support connection to the winch when tensioning mooring chains. Cranes also support connection of the mooring to synthetic fibre lines and eventual hook-up to the floating offshore wind turbine.
- Tensioners are used to obtain the necessary tension in the mooring line to test anchors and to pre-tension mooring systems.
- Marker buoys are used to indicate positions of submerged materials. Some designs can automatically rise to the surface when instructed.

What's in it

- I.4.1 Anchor-handling vessel
- Cranes
- Drills
- Grout spreads
- Marker buoys

- Pile hammers
- Pumps
- O.2.2.2.1 Remotely operated vehicle
- Stern rollers
- Winches

I.5 Floating offshore wind turbine assembly

Function

The assembly, pre-commissioning, and storage of floating offshore wind turbines that are ready for tow-out and installation.

Figure 39 Floating offshore wind turbine final assembly taking place at port. ***Photo of the Kincardine Offshore Wind Farm project courtesy of Principle Power.***

What it costs

About £31 million for a 450 MW floating offshore wind farm.

Who supplies this

This work is usually contracted to either the wind turbine supplier, or to a wind turbine installation and commissioning contractor. The contractor normally provides supervisory input and subcontracts the work to a technician services company.

Key facts

Offshore wind developers have become used to assembly and installation rates of about two turbines per week for fixed wind farms, enabling the turbines for a 1 GW fixed offshore wind farm to be installed in a single season. An output rate of at least one floating offshore wind turbine per week is needed for a 450 MW wind farm with 30 turbines to be installed in one season, given typical constraints including weather.

Some designs of semi-submersible floating substructures need pre-assembly at the construction port. The mass of a primary structure, typically in excess of 3,500 t, is greater than the maximum lift capacity of the largest mobile cranes. Rail systems or self-propelled modular transporters (SPMTs) are options for moving on land. Ring cranes, vessel-mounted cranes, or semi-submersible barges can be used to move a primary structure from land into water. A dry dock addresses both issues but large dry docks are scarce. Other components, such as secondary steel or transformers, may be pre-assembled at the construction port too.

The major turbine components are moved to the quayside, normally using SPMTs. Some pre-assembly work is expected to be performed at this stage, for example installing electrical equipment in the base of the turbine tower. Major turbine components have such high mass that they are normally stored, and pre-assembly work carried out, on specially reinforced pedestals.

The floating substructure is brought from wet storage to the quayside using harbour tugs.

The major turbine components are then assembled onto the floating substructure in a process known as final assembly or turbine integration. This activity can either be completed with a landside crane located on the quayside or by a temporary jack-up crane vessel alongside the quay. Ballasting the substructure so that it rests on a mattress laid on the sea bed improves its stability for lifting activities.

We expect towers to be assembled onto the floating substructure one section at a time, to avoid creating a load on the lifting equipment that is even greater than the nacelle weight. If lift capacity is not a restriction, the tower could be assembled on the quayside and lifted as one unit. The next stage is to install the nacelle and finally the turbine blades, normally one at a time.

The assembled floating offshore wind turbine is pre-commissioned at port to the greatest possible extent to reduce offshore commissioning work. This involves mechanical and electrical testing of the various subsystems.

Wet storage is required prior to tow-out of assembled floating offshore wind turbines. Developers typically plan for a stock of around 20% of the completed project in wet storage, so that offshore installation can proceed smoothly and take best advantage of weather windows. This is in addition to the wet storage required for inbound floating substructures.

What's in it

- I.8 Construction port
- Jack-up crane vessel
- Quayside crane
- Tower pedestal

- Transport and storage frames for major components including nacelles, blades, and tower sections

I.5.1 Heavy lifting and moving equipment

Function

Equipment to move and lift major turbine components for pre-assembly, and for assembly with the floating substructure at the quayside of the construction port.

Figure 40 A landside crawler crane lifting a nacelle onto a floating substructure. ***Image courtesy of Port Pictures / Danny Cornelissen. All rights reserved.***

What it costs

About £13 million for a 450 MW floating offshore wind farm.

Who supplies this

Land-based cranes and moving equipment: Ainscough, Mammoet, Sarens and Weldex.

Jack-up cranes: DEME, Fred. Olsen, Jan de Nul, Seajacks, Seaway 7, and Van Oord.

Key facts

Heavy loads are generally moved around port quaysides using SPMTs.

The main options for lifting turbine components onto floating substructures are either land-based ring cranes or using vessel-mounted cranes (on jack-up vessels). The height and reach requirements to lift a nacelle onto the tower of a floating substructure are significant and push mobile cranes to the limits of their lifting capabilities. A minimum crane capacity of 800 t with a hook height of approximately 160 m and reach of 30 m from the quayside is required to lift 15 MW nacelles into place on the reference semi-submersibles.

We expect that most floating offshore wind construction ports will use a wind turbine installation jack-up vessel in port for heavy lifting operations of turbine components. Older jack-up installation vessels or barges may be used providing they have sufficient reach and crane capacity. Additional hook height can sometimes be provided by jack-up legs depending on their length with respect to the depth of the quayside. The sea bed at the quayside should be levelled and have sufficient load bearing capacity for the jack-up legs.

Some ports might invest in landside cranes. Landside cranes can either be semi-permanent ring cranes or crawler cranes.

Specialised lifting equipment is required under the hook to ensure that loads are level when lifted, wind-induced movement is minimised, and final alignment is accurate. For nacelles, blades and towers, this equipment is normally designed and provided by the wind turbine supplier.

What's in it

- Crawler crane
- Jack-up, or barge-mounted crane
- Ring crane
- Specialised lifting equipment
- SPMTs

I.5.2 Technician services

Function

Skilled personnel operating plant, such as cranes and SPMTs, for pre-assembly and assembly of the turbine with the floating substructure. Dedicated personnel complete pre-commissioning in port and final commissioning at site once the floating offshore wind turbine has been towed-out and hooked-up.

What it costs

About £2 million for a 450 MW floating offshore wind farm.

Who supplies this

Global Wind Service, James Fisher Marine Services, Semco Maritime, Swire Energy Services, Windhoist and Worley Services.

Key facts

Turbine pre-assembly and assembly onto floating substructures is undertaken jointly by the turbine supplier technicians and the installation contractor. The turbine supplier is usually responsible for the lifts of the turbine components along with mechanical and electrical completion and final commissioning.

Members of the turbine supplier team are expected to travel with the turbine on board the AHV to monitor the transit and accelerations of the turbine during tow-out and hook-up.

What's in it

- Specialist assembly equipment including bolt tensioning, bolt torquing and electrical testing
- Landside generators
- Technicians

I.6 Floating offshore wind turbine installation

Function

Tow-out of an assembled floating offshore wind turbine to site, hook-up to mooring lines and array cables, and the final commissioning of the installed floating offshore wind turbine.

Figure 41 An assembled floating offshore wind turbine starting its tow-out for the WindFloat Atlantic project. *Photo of the WindFloat Atlantic project courtesy of Principle Power/Ocean Winds.*

What it costs

About £24 million for a 450 MW floating offshore wind farm.

Who supplies this

Boskalis, Bourbon Offshore, Maersk, Saipem and Seajacks.

Key facts

Floating offshore wind turbines are towed from the construction port to the offshore site with a primary AHV and smaller support vessels.

The floating offshore wind turbine is hooked-up to a pre-installed mooring spread once it arrives at site with the aid of the towing vessels.

The array cable is either connected to the floating offshore wind turbine once it arrives at site or later during post lay operations.

Tow-out and hook-up is expected to be performed by an offshore EPCI contractor, because the vessels are the largest part of the cost build up.

Final commissioning involves commissioning the assembled floating substructure with its mooring and array systems, and the final commissioning of the wind turbine. It is expected to be split between the EPCI contractor for the hook-up and floating substructure, and the wind turbine supplier for the wind turbine.

What's in it

- I.6.1 Tow-out
- I.6.2 Mooring line hook-up
- I.6.3 Array cable hook-up
- I.6.4 Final commissioning

I.6.1 Tow-out

Function

Tow-out of the assembled floating offshore wind turbine from the construction port to the offshore wind farm site.

What it costs

This is included in the floating offshore wind turbine installation contract.

The tow-out operation is usually completed by three AHVs that have a combined day rate of about £130,000.

Who supplies this

Boskalis, Bourbon Offshore, DOF Subsea, Maersk and Saipem.

Key facts

The floating offshore wind turbine is towed out to site using a primary towing AHV with minimum bollard pull of around 200 t.

These operations are usually supported by two trailing AHVs during tow-out and positioning activities at site.

The operation is usually completed in fair weather with a maximum significant wave height (Hs) of between 1 and 1.5 m and mean wind speeds below 14 m/s. A weather window of sufficient length is required, so that the assembled floating offshore wind turbine could be towed back to port in the case of problems with hook-up. Transit speeds of between 3 and 4 kn are used. This is limited by a number of factors including vessel fuel consumption, towing capacity and weather.

Transit distance is a limiting factor in the tow-out of floating offshore wind turbines and this is a key consideration for construction port and wind farm site selection.

Prior to tow-out, the floating substructure is normally ballasted to add stability in a location with adequate water depth for the increased draft. As the reference design is a steel semi-submersible, this involves pumping water onboard.

A constraint during transportation and installation is the nacelle acceleration limit defined by the turbine supplier to avoid damaging the turbines and invalidating warranties. This is typically about 0.5 g.

The channel depth between the port and the project site is one factor which influences the choice of substructure type and construction material.

What's in it

- I.4.1 Anchor-handling vessel
- Support tugs
- I.5.2 Technician services

I.6.2 Mooring line hook-up

Function

Hook-up and tensioning of mooring lines to the floating substructure in its final position.

What it costs

This is included in the floating offshore wind turbine installation contract.

Who supplies this

Boskalis, Bourbon Offshore, DOF Subsea, Maersk and Tronds Marine AS.

Key facts

A three-column semi-submersible typically has a three-point mooring spread, as a minimum, and at least one of these lines includes an in-line tensioner.

Any sections of mooring line that have not been pre-installed are installed. For example, codes do not allow fibre rope lines to be laid on the sea bed for extended periods, so they cannot be installed a year in advance. ROVs are used to make any remaining connections between mooring line sections and support the connection to the anchor-handling winch to bring the upper section of mooring chain on deck. The upper chain is connected to one of the three mooring points on the floating substructure and the winch slowly feeds the chain back out into the water and is eventually disconnected from the mooring chain. This same process is completed for the second and third mooring lines. At this point there is some slack in the lines.

To tension the system, the free end of the active lower chain section is retrieved from the sea bed with the support of an ROV, as before. Vertical loads are applied to the active side using the winch and crane of the AHV. This gradually increases tension throughout the entire mooring spread as the active side of the third line slowly passes through the tensioner mechanism. The active side is lowered, disconnected, and laid to rest on the sea bed once the required line tensions are reached. The use of an in-line tensioner can significantly reduce the tug bollard pull required to reach the mooring line pre-tension, depending on the geometry of the mooring system and the position of the tensioner.

What's in it

- I.4.1 Anchor-handling vessel
- In-line tensioner
- B.3.2 Mooring chains
- O.2.2.2.1 Remotely operated vehicle
- Support tugs
- I.5.2 Technician services
- Vessel crane
- Winch

I.6.3 Array cable hook-up

Function

Hook-up and connection of the array cables to the floating substructure. This may take place directly after mooring hook-up or later if array cables are laid after the floating offshore wind turbine has been hooked up to its mooring system.

What it costs

This is included in the floating offshore wind turbine installation contract.

Who supplies this

Boskalis, Bourbon Offshore, DOF Subsea, Global Offshore, Maersk, Société de Dragage International, Subsea 7 and Tronds Marine AS

Key facts

Array cables are either pulled directly into the floating substructure, or into a pre-installed buoyant junction box.

Pre-laid dynamic or factory jointed cables that were left to rest on the sea bed are retrieved with ROVs and transferred to the crane and winch of the support vessel. Buoyancy modules are attached at this point to form the lazy-wave shape of the dynamic section.

Platform supply vessels or multipurpose offshore vessels with a motion compensated gangway are suitable. Crews are transferred to the floating offshore wind turbine via the gangway to complete cable pull-in, termination, and connection within the turbine.

For pre-laid cables that are connected using buoyant junction boxes, the ROV and support vessel retrieves the buoyant junction box which is then pulled in and mated to the corresponding part of the junction box on the floating substructure. Electrical connection is made in the junction box.

In cases where wet or dry mate connectors are used, dynamic cable lengths may be installed at the array cable hook-up stage. This requires a support vessel with a cable carousel of sufficiently capable carrying pre-cut dynamic lengths.

- If a dry mate connecter is used the vessel needs to retrieve the static cable or pre-installed connector from the sea bed. The crew on board the vessel then make all connections within the connector, including power and communications, before lowering the made-up connector back to the sea bed.
- For wet mate connections it is expected that the pre-laid static cable end will have a connector pre-installed. A second connector plate is connected to the dynamic cable end and lowered to the sea bed for connection with ROV.

Two pull-ins, terminations and connections are completed at each floating offshore wind turbine where a turbine is located in the middle of a string, for the incoming and outgoing array cables.

What's in it

- B.1.1 Array cable
- Buoyant junction box
- I.2.5 Cable pull-in
- B.1.3.4 Dry mate connector
- Electrical testing and termination
- Motion compensated gangway
- O.2.2.2.1 Remotely operated vehicle
- Support vessel
- I.5.2 Technician services

- Vessel crane
- B.1.3.4 Wet mate connector
- Winch

I.6.4 Final commissioning

Function

Final commissioning is a set of mechanical and electrical checks and tests on the installed floating offshore wind turbine. It results in all systems having been put to work in a safe manner prior to handover of the installed floating offshore wind turbine to the client.

What it costs

This is included in the wind turbine supply contract and substation supply contract.

Who supplies this

Final commissioning is expected to be split between the EPCI contractor for the array cable installation and hook-up, and the wind turbine supplier for the wind turbine.

Key facts

As much pre-commissioning as possible is performed on the various subsystems prior to offshore installation, to minimise the time and cost of final commissioning offshore.

The key steps in final commissioning the offshore substation and cabling include visual inspection, mechanical testing, protection testing, electrical insulation testing, pre-energisation checks, trip tests and load checks.

The key steps of the final commissioning of the turbine include:

- Check of installation activity and documentation
- Mechanical and electrical completion
- Check of communication systems (SCADA, VHF radio)

- Energisation of all subsystems
- Testing of each link in safety and emergency system chains
- Exercising of all safety-critical and auxiliary systems
- Slow rotation of the rotor to confirm balance and smooth operation of the drive train
- Overspeed sensor and other safety-critical checks
- First rotation then first generation and checks on normal operation of all systems, and
- Checks on critical components and connections after a period of attended operation, then after a longer period of unattended operation.

If the installed floating offshore wind turbine has not been connected to the grid then final commissioning of the turbine can be carried out using a generator and a load bank, or power from a service operation vessel (SOV).

Even after first generation, it is routine to have several outstanding work lists for each turbine and substation detailing issues that need to be addressed before handover to the customer. Handover also normally requires demonstration of performance and reliability over an agreed length of time.

What's in it

- Electrical testing equipment
- Generator
- Load bank
- I.5.2 Technician services

I.7 Inbound transport

Function

Shipping of major items from their manufacturing ports to the construction ports. These include nacelles, blades, towers, floating substructures (either complete or as major sections), moorings, anchors, cables, and offshore substations.

What it costs

About £3.9 million for a 450 MW floating offshore wind farm.

Who supplies this

Blue Water Shipping, Bourbon, Boskalis, Cadeler, Coordinadora Internacional De Cargas, DEME, Jumbo Shipping, Roll Group, SAL Heavylift, Saipem, Seaway 7, TechnipFMC, and United Wind Logistics.

Key facts

Turbine components are brought from several manufacturing locations to the construction port. Turbine suppliers operate dedicated transport vessels. These vessels are becoming increasingly specialised as blades and nacelles increase in size and mass.

Load-in operations depend on the component and the transport vessel type. Turbine suppliers and subsidiary manufacturers often use roll-on roll-off (ro-ro) vessels to minimise crane lifts during load-in. SPMTs are often used to transport components to the quayside and are sometimes used to move them onto vessels. Alternatively, land-based cranes may be used, or some vessels have their own cranes (see I.5.1 for further information).

Complete floating substructures are transported to the construction port either by towing with AHVs or on floating semi-submersible cargo vessels.

- For towing, a minimum of two AHVs are required, and towing can only commence if there is an accessible port in case of an emergency within the shipping weather window.
- Semi-submersible vessels can reduce the overall transit time but require careful load-out at the assembly port and load-off by submerging the delivery vessel at the construction port, where sufficient depth of around 20 m is required. As production rates increase it is expected that steel semi-submersibles will be shipped in sections for assembly at the construction port, due to their large footprints. It is expected that concrete semi-submersibles will be manufactured close to the construction port as their high mass will increase the cost of shipping.
- Harbour tugs or small AHVs position the floating substructure in the wet storage area and hook-up to pre-laid mooring spreads. Alternatively, the floating substructure is moved directly to the quayside in preparation for final assembly.

Floating substructures can also be transported to the construction port in sections or components, where final assembly takes place (see I.5 for further information).

Other components that are too large for transport by road and rail use barges, ro-ro vessels or cargo vessels. The choice is driven by the size of the load and the sea conditions expected. These include parts for the anchor and mooring system, the dynamic array cable system, and items that might be pre-assembled into the floating substructure such as secondary steel, transformers, and circuit breakers.

- Barges are suited to inshore shipping and calmer offshore waters but have relatively small capacities.
- Ro-ro vessels have short turnaround times and may be used in more challenging seas. Some are specifically designed to suit particular wind turbine suppliers' needs.
- Cargo vessels are generally larger, with higher capacities, and are used for deep-sea shipping. Sea fastenings need to be stronger for rougher seas.

Transport, ro-ro and lifting operations are overseen by turbine supplier representatives, vessel crew and port stevedores to guard against damage.

What's in it

- Barges
- Cargo vessels
- Landside cranes
- Ro-ro vessels
- Semi-submersible vessels
- SPMTs
- Stevedores
- Trucks and trains (for smaller components)

I.8 Construction port

Function

The construction port is where inbound components are marshalled and stored, the turbine is pre-assembled, and the turbine is finally assembled with the floating substructure. Wet storage areas are required for the marshalling of floating substructures and for marshalling of assembled floating offshore wind turbines. A construction port is one that is only used for marshalling components.

Figure 42 The Port of Cromarty Firth used as the construction port for part of the Kincardine project. ***Image courtesy of Port of Cromarty Firth. All rights reserved.***

What it costs

This is included in installation contracts.

Who supplies this

Construction ports used for early pre-commercial floating projects: Aberdeen (UK), Cromarty Firth (UK), Dundee (UK), Ferrol (ES), Lorient (FR), Nouvelle (FR), Rotterdam (NL), Skipavik-Gulen (NO) and Stord (NO).

Key facts

Construction port requirements for a 450 MW project are typically:

- Between 15 and 20 ha suitable for lay down and pre-assembly of turbines
- Between 10 and 12 ha of wet storage for storing floating substructures prior to final assembly, and for storing assembled floating offshore wind turbines prior to tow-out
- Quayside length of around 500 m with load bearing capacity ranging from 40 to 100 t/m^2 and adjacent access
- Quayside water depth of between 12 and 20 m to accommodate the draft of floating substructures and semi-submersible transport vessels
- Water access to accommodate delivery vessels for floating substructures and turbine components. These are up to 160 m length, 45 m beam and 6 m draft with no tidal or other access restrictions
- No air draft restrictions, to allow tow-out of assembled floating offshore wind turbines with tip heights of about 250 m, and
- As close as possible to the installation site to minimise the time to tow-out and sensitivity to weather windows, although the distance depends on many factors including the location of ports relative to the site, the cost to upgrade ports (where necessary) and the cost of fuel.

Large areas of land are required due to the space taken when turbines are stored lying down on the ground.

Sites with greater weather restrictions or for larger scale construction may require an additional lay-down area of up to 30 ha.

Wet storage is required to temporarily store floating substructures delivered to the construction port before final assembly with the turbine at the quayside. This storage can also be used prior to tow-out of the assembled floating offshore wind turbines with seafaring AHVs.

Separate ports may be used to fulfil the functions of a construction port for the floating offshore wind turbine, the mooring system and the cable system.

Different construction ports may be used to feed floating substructures and wind turbines, separately, to a wind farm if new methods are introduced for final assembly of turbines directly onto moored floating substructures at site. This would require semi-submersible or capable monohull heavy lift vessels to install the turbine as site water depths are not suitable for jack-up installation vessels.

An alternative to using quayside final assembly of turbines and floating substructures is to assemble them in a dry dock, but there are few dry docks which have suitable width for a typical three-column semi-submersible.

What’s in it

- Bunkering facilities
- Cranes
- Jetties for crew transfer vessels (CTVs) (if required to support installation)
- Lay-down area
- Personnel facilities
- Pre-assembly area
- Quay

- Wet storage area
- Workshops

I.9 Offshore logistics

Function

Offshore logistics involves coordination and support of offshore installation and final commissioning activities.

What it costs

About £1 million for a 450 MW floating offshore wind farm.

Who supplies this

Asco, DNV, Global Wind Service, LOC Renewables, Osprey, Rhenus Group, PSG Marine & Logistics, SeaRoc, Schmidbauer and Ventolines.

High-level coordination is typically undertaken by the developer.

Key facts

Offshore logistics covers all the work needed to ensure that construction proceeds smoothly, safely and on time.

Construction management covers a wide range of services including contract management, health and safety and marine coordination. In many cases contractors are embedded in the construction management team, and this may include sole traders. In addition, to fulfil the insurer's requirements, a marine warranty surveyor (MWS) has to be appointed. The MWS ensures that all activities are compliant with the approved procedures and delivers the Certificate of Approval.

Specialist software tools are available to plan and monitor offshore activity.

Weather and metocean forecasting services provide visibility of weather windows a few days in advance. While meteorological buoys are typically owned and operated in the UK by the Met Office, third-party providers with their own forecasting algorithms also offer services.

Support vessels include guard vessels (potentially drawn from local fishing fleets), CTVs and accommodation vessels. These vessels may be contracted by the developer or the marine contractor.

What's in it

- I.9.1 Sea-based support
- I.9.2 Marine coordination
- I.9.3 Weather forecasting and metocean data
- I.9.4 Marine safety and rescue

I.9.1 Sea-based support

Function

A number of vessels are used to support the installation process. These may include AHVs, CTVs, ROV handling vessels, SOVs and walk-to-work vessels.

What it costs

About £640,000 for a 450 MW floating offshore wind farm.

Who supplies this

Vessel manufacturers: Alicat, Arklow Marine Services, Damen, Diverse Marine, Integrated Wind Solutions, Maersk, Wagenborg and Wight Shipyard.

Vessel operators: Fred. Olsen, HST Marine, Mainprize Offshore, Maersk, Turner Iceni, Siem Offshore, Van Oord, Wind Energy Marine, and Windcat Workboats.

Key facts

Specialist vessels are used for crew transfer to the wind farm for installation and commissioning tasks. CTVs are used if the wind farm is close to shore. Wind farms farther from shore use SOVs. Both types of vessels are regularly used in offshore wind farm maintenance.

ROV support vessels are 80 to 100 m long DP2 vessels with a moon pool and deck crane.

What's in it

- Barge
- O.4.1 Crew transfer vessels
- O.2.2.2.1 Remotely operated vehicle

I.9.2 Marine coordination

Function

Marine coordination is necessary to manage heightened marine traffic as well as multi-vessel activity on an offshore construction site.

What it costs

About £210,000 for a 450 MW floating offshore wind farm.

Who supplies this

Marine coordination is usually carried out by the developer or a subcontractor.

Suppliers of marine coordination: Asco, James Fisher Marine Services, Royal Dirkzwager, SeaRenergy, SeaRoc, Specialist Marine Consultants, Systematic, VisSim and WindandWater.

Key facts

A marine coordinator, usually located at the base harbour or operations base, is responsible for the coordination, control, and exchange of information between all contractors working on the site. A marine management software system is used to plan and monitor vessel and personnel movements.

The main tasks of the marine coordinator include:

- Monitoring all vessel and personnel movement (as well as helicopter) from, to and inside the offshore wind farm perimeter
- Ensuring no conflict from simultaneous operations
- Ensuring the authorisation and access of appointed persons on the site, and
- Communicating with all vessels and helicopters.

What's in it

- Marine coordination centre
- Marine management system software

I.9.3 Weather forecasting and metocean data

Function

Weather forecasts are needed for short-term planning of offshore activities, for example vessel transfers and lifts. The closer the forecast is to the activity, the more reliable it gets. Metocean data recordings are used to provide real time data to support offshore activity, to verify forecast tools and to resolve disputes regarding weather downtime.

Key metocean parameters that impact installation and commissioning activities are wind speed, wave height and current.

What it costs

About £70,000 for a 450 MW floating offshore wind farm.

Who supplies this

Anemometers and lidars: AXYS Technologies, EOLOS, Gill Instruments, Leosphere, ZX Lidars and Wood Group.

Current and wave buoys: AXYS Technologies, OSIL Partrac and RS Aqua.

Weather forecast services: Fugro, Met Office, Kjeller Vindteknikk, MetoGroup, StormGeo and Vento Maritime.

In addition, the vessel contractor generally provides wind measurements (for example via anemometer mounted on crane boom or lidar).

Key facts

Weather plays a crucial role in offshore installation and commissioning activities as it has an influence on the sequence and duration of planned activities and may lead to delays, which result in elevated costs. This is because all offshore activities have weather limits within which they can be conducted safely and exceeding these would be unsafe.

Weather forecasts are generated through global meteorological models that may be improved in their accuracy with finer resolution local models and feedback of actual data.

The weather forecast supplier usually offers several options, both in the number of forecasts per day as well as forecasts for the different locations. For example, forecasts for the base harbour and the offshore site or a complete forecast for base harbour, the offshore site and transit route.

Forecasts usually include several different meteorological parameters (for example wind speeds at different heights, wave and swell height and wave period) as well as general weather information (for example visibility, lightning risk, fog, water and air temperature and rain). The forecasts are used to plan shipping, lifting and other installation activities based on when weather windows are available.

Wind parameters are usually measured with a lidar (on a fixed or floating meteorological station) or an anemometer (rotary or ultrasonic) on a fixed metrological station with tall mast. The advantage of the lidar is that wind speed and direction at different heights can be determined.

Ocean parameters can be measured with a wave buoy or current meter although there is a trend towards complete systems that combine both wave and current measurements.

What's in it

- Anemometer
- Current meter
- Lidar
- Wave buoy

- Weather forecast report (and online access)

I.9.4 Marine safety and rescue

Function

A set of capabilities used to assure the safety of the workforce and offshore assets during marine operations.

What it costs

About £100,000 for a 450 MW floating offshore wind farm.

Who supplies this

Esvagt, MRT, Resolve Marine, Seacroft Marine, Systematic, Ultramap and Viking Life Saving Equipment.

In the UK NFFO Services, the commercial division of the National Federation of Fishermen's Organisations, provides guard vessel services using the fishing vessels of its members.

Key facts

Safety is a crucial factor in any marine operation in offshore wind. All vessels carry and adhere to general safety and emergency response plans, both for general vessel activity and for project-specific activities. The vessel conducts frequent safety drills to ensure crew are prepared for emergencies.

Guard vessels are used on site to spot vessels which should not be there because they pose a risk to the assets or the activities taking place.

Various software solutions have been developed to assist the safe planning and tracking of marine activities. These include:

- Tracking the location of each member of the offshore workforce
- Planning and tracking the movement of vessels working on the project, and

- Tracking other vessels' speed and location via Marine AIS data and proactively contacting the vessel or its owner should the activity suggest a risk from anchoring or collision.

Remote emergency medical services consist of a remote doctor or paramedic who can provide 24/7 support to onsite first aiders via voice and video calls. Actual rescue services for injured personnel are carried out by either small vessels or helicopters. Emergency medical and rescue service providers can cover multiple wind farms and developers.

New technologies are emerging to improve marine safety and rescue. This includes systems to automatically identify people in the water and technology to retrieve them onto a vessel.

What's in it

- Emergency medical rescue services
- Emergency medical support services
- Guard vessels
- Specialist marine planning and tracking software

O Operations and maintenance

Function

Operations and maintenance (O&M) are the combined functions which, during the lifetime of the wind farm, support the ongoing operation of the wind turbines, balance of plant and associated transmission assets. O&M activities formally start at the wind farm construction works completion date.

The focus of these activities during the operational phase is to ensure safe operations, to maintain the physical integrity of the wind farm assets and to optimise electricity generation.

What it costs

About £32 million per annum for a 450 MW floating offshore wind farm. This includes insurance, environmental studies, compensation payments and other internal asset owner costs (not itemised in sections below).

Who supplies this

The wind farm owner oversees and fulfils overall site operations activities.

In terms of wind turbine planned maintenance in response to faults, wind turbines are typically under warranty for the first three to ten years of operations and the wind turbine suppliers offer a service level agreement during this period to provide turbine maintenance.

After this initial warranty period, the wind farm owner may maintain the wind farm using an in-house team, contract to a specialist company, or develop an intermediate arrangement where turbine technicians transfer to the wind farm owner at the end of the warranty period.

Key facts

The focus of O&M is to maximise the financial return from the owners' investment. Owners aim to optimise the balance between operational expenditure and turbine yield. By scheduling downtime during the low wind speed summer months, owners can secure high availability during the winter months when wind speeds and energy outputs are typically higher. Contractual arrangements which award energy production are increasingly common.

Turbine availability is the percentage of time the wind turbine is ready to produce power if the wind speed is within the operational range of the turbine. Modern onshore turbines have a technical availability of around 98%. The performance of offshore wind turbines has improved with optimised design, and offshore turbines often have availabilities in a similar range to onshore. The planning of logistics and access is vital to securing high availabilities. Where there are access restrictions then availability may be in the range 95 to 98%.

Operational support is provided to the wind farm 24/7, 365 days a year including responding to unexpected events and turbine faults, weather monitoring and live turbine monitoring. Outside normal operating hours this support is provided from remote control rooms which monitor wind farm SCADA data.

Maintenance includes scheduled and unscheduled activities and requires the regular transfer of personnel and equipment to the wind turbines and offshore substation. Safe access to the turbines is a critical area for further focused innovation.

Repairs and replacement of major turbine components, including the blades, are carried out by the turbine supplier or, less commonly, by specialist 3rd party providers.

In the UK, transmission assets (substations and export cables) are transferred to an Offshore Transmission Owner (OFTO) within 18 months of wind farm commissioning. The OFTO may contract some maintenance functions to the wind farm owner because it has onsite personnel and has a strong interest in minimising transmission downtime. In other European territories, typically a transmission operator is responsible for building the offshore transmission.

What's in it

- O.1 Operations
- O.2 Maintenance
- O.3 Major repair
- O.4 Offshore vessels and logistics
- O.5 O&M port

O.1 Operations

Function

Operations is the management of the asset such as health and safety, control and operation of the asset including wind turbines and balance of plant, remote site monitoring, environmental monitoring, electricity sales, administration, marine operations supervision, operation of vessels and quayside infrastructure, management of spares and equipment, and other back-office tasks.

What it costs

About £11 million per annum for a 450 MW floating offshore wind farm. This includes training, onshore, and offshore logistics support and management, overheads, health and safety inspections and insurance.

Who supplies this

The owner of the wind farm typically creates a special-purpose vehicle to operate the project. This may have several shareholders, one of which is likely to take a lead role.

Operations tasks for offshore wind farms are typically provided by the majority wind farm owner.

Some aspects of wind farm operations are contracted to companies such as Deutsche Windtechnik, James Fisher Marine Services, Natural Power, and Worley.

Key facts

An onshore control room provides access, via SCADA and other systems, to detailed real-time and historical data for the wind turbines, substation, met station, offshore crew, and vessels. Systems ensure that the operations duty manager knows where all personnel and vessels are located. This control room is often responsible for the monitoring of multiple sites.

Wind farms are monitored remotely on an ongoing basis using SCADA and condition monitoring systems and periodically by way of active inspections, including inspections of subsea infrastructure.

A senior authorised person (SAP) is available at all times with coordination responsibility for the switching operations of all high voltage equipment.

Review of SCADA data and prognostic condition monitoring can help to highlight preventative maintenance before failure occurs. The industry is steadily adopting more advanced data-driven approaches to maximising asset value, including the increased use of performance analytics, performance benchmarking, digital twins, and integrated digital systems.

In addition to hardware-related activity, environmental monitoring to understand the effect of the wind farm on the local environment and wildlife is also carried out.

Wind farms can be broadly categorised as operating primarily from an onshore base using CTVs for access, or from an SOV. In both cases, helicopters may also be used in addition to CTVs and SOVs.

In practice, wind farm operators adopt a flexible approach, particularly during peaks of activity. Careful planning of routine and unscheduled activities with due consideration of weather conditions and availability of spares and specialist vessels is critical.

For groups of smaller wind farms located in the same geographical area, it can be cost effective to monitor and control them all from a single operation base.

What's in it

- O.1.1 Operations control centre
- O.1.2 Training
- O.1.3 Onshore logistics

O.1.1 Operations control centre

Function

The operations control centre monitors the performance of the wind farm and co-ordinates any maintenance work required.

What it costs

About £540,000 per annum for a 450 MW floating offshore wind farm.

Who supplies this

Wind farm owners establish their own operations control centres for each wind farm.

Key facts

The operations control centre requires a team of people with skills and experience in:

- Marine operations
- Monitoring of the wind turbines, floating substructure, mooring system, and array connections, and
- Onshore supporting roles, including:
  - Equipment management
  - Grid/OFTO interface
  - Health and safety
  - Logistics management
  - Marine coordination
  - Monitoring and resetting
  - Parts management
  - Weather watch, and
  - Work planning.
- A set of specialist software applications is used to help them perform their roles in the most effective manner.

What's in it

- Qualified staff with experience in co-ordinating marine operations, infrastructure monitoring and onshore logistics
- Specialist software applications

O.1.2 Training

Function

Training ensures that O&M personnel are qualified to fulfil the roles needed by the wind farm while ensuring their own safety and those of colleagues.

What it costs

About £1 million per annum for a 450 MW floating offshore wind farm.

Who supplies this

AIS, ARCH, B&FC, CWind, Heightec, Maersk Training, MRS Training and Rescue, National Wind Farm Training Centres, Offshore Marine Academy, ProntoPort and RelyOn Nutec.

The Global Wind Organisation (GWO) training standards are now widely adopted in the offshore wind industry. The GWO is a non-profit body founded by leading wind turbine suppliers and operators.

Key facts

Training is related to both technical aspects and to health and safety skills and awareness.

Health and safety certificates required by personnel on the wind farm site include:

- Electrical safety awareness
- Emergency first aid and advanced medical training
- Lifting and hoisting
- Manual handling
- Offshore survival training, including marine transfer
- Wind turbine rescue
- Working in confined spaces, and
- Working at height.

The technical training required is dependent on the requirements of the client, but as a minimum covers specific technician training for the relevant turbine model.

Other key training qualification requirements includes operational safety rules for high voltage switching and wind turbine operations

What's in it

- Certification
- Training courses
- Training examinations

O.1.3 Onshore logistics

Function

Onshore logistics provides parts and equipment to support wind farm operations, using quayside infrastructure, warehousing, lifting equipment, logistics and operational planning.

What it costs

About £540,000 per annum for a 450 MW floating offshore wind farm.

Who supplies this

Onshore logistics are coordinated by the wind farm operators. The wind farm owner typically occupies quayside facilities, operating on a long-term lease with the owner of the port infrastructure, to provide onshore logistics services.

Key facts

Port facilities are required to be flexible to accommodate variable demand with maintenance campaigns and site activities. Ideally, the warehousing and logistics buildings are close to the quayside to minimise the time loading support vessels.

24/7 access from a chosen port in all states of tide increases flexibility to perform maintenance operations without delay to enable weather windows to be exploited. This can require port agreements to include requirements for dredging to maintain adequate water depths.

A 450 MW wind farm employs up to about 50 people onsite, of which about half are turbine technicians. The availability of skilled and experienced technicians is a crucial factor in the successful operation of an offshore wind farm for wind farm owners and operators. O&M facilities need 24/7 access, 365 days a year.

As well as the port facility, operators use remote land-based support, such as specific engineering advice and support, performance monitoring and 24/7 control room monitoring.

An onshore base consists of:

- Administration facilities and operations room
- Lifting equipment, for example forklifts (600 kg) and small cranes (1 t) to move components from the harbour to the vessel
- Workshop facilities, workbench areas and tool storage
- Stores, with small components that do not need specialist vessels to facilitate use
- Wet and dry rooms, with space for personal protection equipment
- Oil store, gas bottle store and waste management facilities
- Fuel bunker, and
- Parking spaces.

What's in it

- Facilities management

O.2 Maintenance

Function

Maintenance activities ensure the ongoing operational integrity of the wind turbines and associated balance of plant in response to faults, either proactively or reactively.

What it costs

About £20 million per annum for a 450 MW floating offshore wind farm.

Who supplies this

Maintenance activities are provided by a combination of the owner's in-house resources, wind turbine suppliers and third-party service providers.

Key facts

There is considerable focus in the industry on optimising maintenance activities to reduce OPEX whilst also achieving the targeted levels of availability and reliability. This optimisation is best achieved by taking a lifetime view of the project economics, focussing on the LCOE. Operational management teams consider the whole operational system to achieve this.

What's in it

- O.2.1 Turbine maintenance
- O.2.2 Balance of plant maintenance
- O.2.3 Statutory inspections

O.2.1 Turbine maintenance

Function

Effective turbine maintenance ensures the long-term productivity of the turbines.

What it costs

About £14 million per annum for a 450 MW floating offshore wind farm.

Who supplies this

The wind turbine supplier, during the defect notification period (DNP) and for the duration of any agreed contract beyond the DNP.

The wind farm owner may seek to bring maintenance and repair capability in-house or to engage an independent service provider (ISP). This typically requires agreement with the manufacturer for the supply of spares, software systems and specialist expertise.

ISPs include Deutsche Windtechnik, James Fisher Marine Services, Swire Energy Services and Worley.

Key facts

The requirements for turbine maintenance are similar for floating and fixed offshore wind turbines. Conducting maintenance in a moving floating offshore wind turbine presents additional challenges for health and safety when moving items and motion-induced sickness. These issues are more significant at height where any low frequency movement of the floating substructure is amplified.

The initial service agreement typically covers the period of the turbine defect warranty, which is usually five years. During this period, turbine technicians are typically employed by the wind turbine supplier. The service agreement may specify that technicians' contracts are transferred to the wind farm owner on expiry. This ensures continuity of staffing and removes technicians' disincentive to relocate to the wind farm site. Some owners employ their own technicians to deliver a proportion of turbine maintenance from the start to build in-house knowledge and capability, in agreement with the provider of the initial service agreement.

Activity is divided into preventive maintenance (scheduled) and corrective repair (unscheduled). The bulk of preventive maintenance is typically carried out during periods of low wind speeds (usually the summer months) to minimise the impact on production. However, this is not always achievable in practice.

Corrective repair is performed in response to unscheduled outages and is often viewed as more critical, due to accruement of downtime until the fault is resolved. The primary skills required are mechanical or electrical engineering, with further turbine-maintenance training often provided by the relevant turbine provider.

Typical maintenance includes inspection, checking of bolted joints and replacement of worn parts (with design life less than the design life of the project).

Unscheduled interventions are in response to events or failures. These may be proactive (before failure occurs) for example responding to inspections or from condition monitoring, or reactive (after failure that affects generation has occurred).

What's in it

- O.2.1.1 Blade inspection and minor repair
- O.2.1.2 Unmanned aerial vehicle

O.2.1.1 Blade inspection and minor repair

Function

Blade inspection and minor repair consists of the inspection of the condition of blades and repairing minor blade issues in a timely and cost-effective manner.

Figure 43 Blade inspection and minor repair being carried out by a rope-access technician. *Image courtesy of Altitec. All rights reserved.*

Who supplies this

Repair service suppliers: Bladefence, Deutsche Windtechnik, GEV, Global Wind Service, Mistras and Worley.

Inspection technology suppliers: ABJ, Cornis, Scoptico and SkySpecs.

Key facts

Blade inspection and minor repair is an area of specific focus in the offshore wind industry. Issues such as leading-edge erosion have been the source of availability issues in the industry, and proactive blade inspection and preventative repair is now widely pursued in response.

Blade inspections are performed by drones equipped with high-resolution cameras, by rope-access technicians or by high-resolution camera equipment located on the transition piece or vessel.

Where minor repairs are required, this is sometimes possible using rope-access teams often using a blade platform suspended from the hub.

Where a blade cannot be repaired in-situ or replaced at site, it is expected to be towed back to port where the major repair or replacement can be undertaken using either an onshore crane or a jack-up vessel.

Blade inspection work typically requires the turbines to be stationary, therefore there is a focus on performing inspection work during the less windy periods of the year to minimise lost energy production.

Specialist expertise is required to undertake damage diagnostics and repair activities.

Automation of blade inspection and damage diagnostics is an active area of innovation, as is the ability run the diagnostics on an operating turbine (that is, without the need for the rotor to be stationary).

What's in it

- Unmanned aerial vehicle
- Rope-access technicians

O.2.1.2 Unmanned aerial vehicle

Function

Unmanned aerial vehicles (UAVs) provide low cost and safer external inspections of turbines.

Who supplies this

Manufacturers: Aerial Vision, ASV Global, DJI and SkyFront.

Operators: Cyberhawk, Esvagt, Force Technology, Perceptual Robotics and SkySpecs.

Key facts

Most UAVs for wind turbine inspection are multi-rotor copter drones.

Drones are typically provided by specialist operators and are rented with qualified pilots.

Drones can perform an inspection in a fraction of the time required for a traditional rope-access inspection.

The drone can be equipped with a digital camera, a thermographic camera, or a combination, depending on the scope of the inspection task. A digital camera provides proof of the visual failures and damages to the tower, nacelle, rotor blades and bolt jointing.

Thermographic inspection is a non-contact and non-destructive inspection method that makes it possible to examine a large area of the blade for structural defects and weaknesses in the blade. With infrared thermography, the drone monitors variations in the surface temperature of the blades.

A number of specialist suppliers supply the industry with integrated drone inspection, image diagnostics and data archiving services.

What's in it

- Data diagnostics, storage, and archiving
- Flight planning

O.2.2 Balance of plant maintenance

Function

Balance of plant maintenance is focused on ensuring the operational integrity and reliability of all wind farm assets other than the wind turbines, including the substation(s), foundations, array cables, export cables, scour protection and corrosion protection systems.

Figure 44 Technicians servicing the floating substructure at the WindFloat Atlantic project. *Photo of the WindFloat Atlantic project courtesy of Principle Power/Ocean Winds.*

What it costs

About £6 million per annum for a 450 MW floating offshore wind farm.

Who supplies this

Acteon, CWind, Fred. Olsen, James Fisher Marine Services and Worley.

Key facts

The balance of plant forms an integral part of the wind farm system. Proactive balance of plant maintenance is a key aspect of a preventative maintenance regime.

Regular inspections of all balance of plant elements are required to ensure emerging issues are highlighted and remedial repair work is planned to avoid loss of generation.

What's in it

- O.2.2.1 Floating substructure monitoring, inspection, and minor repair
- O.2.2.2 Anchors and mooring system inspection and minor repair
- O.2.2.3 Cable monitoring, inspection, and minor repair
- O.2.2.4 Scour monitoring and management
- O.2.2.5 Substation monitoring and maintenance

O.2.2.1 Floating substructure monitoring, inspection, and minor repair

Function

Identify and address corrosion, structural and floating substructure subsystem problems above and below the water line on the floating substructure.

Who supplies this

CWind, Deutsche Windtechnik, Fugro, Global Wind Service, Mistras, Offtech Wind and Strainstall.

Key facts

Monitoring, inspection, and minor repair activities focus on the structural integrity of the substructure, the secondary steelwork, its corrosion protection and the various subsystems used on the floating substructure (see B.2 for further information). This is in addition to statutory inspections.

They are managed by the wind farm owner, although they are often subcontracted to a specialist third party provider.

On some sites, cleaning is needed to remove seabird guano, which can be a serious health and safety hazard.

Routine surveys are likely to be undertaken in the first two years but thereafter on a less frequent basis across the wind farm, until the rate of defects observed justifies more frequent monitoring and inspection. Inspection areas include:

- Corrosion protection systems
- External and internal surfaces
- Joints
- Mooring attachment points

- Subsystems (for example ballasting, auxiliary lights and power systems), and
- Welds.

Activity needing subsea inspections are generally carried out using ROVs. Diving is required only in exceptional circumstances and efforts are being made to maximise the use of safer, remote techniques.

What's in it

- O.2.2.2.1 Remotely operated vehicle

O.2.2.2 Anchors and mooring system inspection and minor repair

Function

Identify and address corrosion and wear that occurs on anchors, mooring lines and jewellery.

Who supplies this

Ashtead Technology, HebDrone, Geo Oceans, InterMoor and Proceanic.

Key facts

Anchor inspection depends on the anchor type (see B.3.1 for further information). Drag embedment anchors are buried in the sea bed and so inspection usually involves checking burial depth. Suction anchors and driven pile anchors are inspected for corrosion where they protrude out of the sea bed.

Mooring chains are either inspected using general visual inspections or close visual inspections, usually using ROVs (see B.3.2 for further information). Chain links are cleaned if this is necessary for inspection.

During inspection, ROVs visually inspect the whole chain lengths, especially at critical points such as touch down points which receive the most wear. They use callipers to take measurements of link diameters and link touch points. The data is then compared to measurements taken during manufacturing.

ROVs can also conduct photogrammetry to build a digital model of the chain to use in fatigue assessments and to monitor wear with time.

Synthetic mooring lines are inspected visually to check for wear and tear, especially at attachment points for buoyancy devices and clump masses.

The frequency of inspections depends on what is being inspected. Chain in the high-load environments like the touch down points may be inspected every six months, or even more frequently, initially. Chain in lower-load environments can be inspected annually or even less frequently. Frequency of inspection also depends on observed failure rates.

Mooring lines are replaced when observed wear breaches limits.

Jewellery such as links are inspected in a similar way to chains (see B.3.3 for further information), whereas jewellery such as buoyancy devices and load reduction devices are inspected visually.

In-line tensioners are inspected visually, but there is little else that can be done to ensure their condition, and their long-term performance has not been proven.

If an anchor or section of mooring line fails, then it is replaced as rapidly as possible.

Early floating offshore wind farms may install load monitoring on mooring lines to understand how actual loads compare with calculated loads and with observed degradation.

What's in it

- O.2.2.2.1 Remotely operated vehicle
- O.2.2.2.2 Autonomous underwater vehicle

O.2.2.2.1 Remotely operated vehicle

Function

Remotely operated vehicles (ROVs) are used to inspect underwater structures.

Who supplies this

Manufacturers: ECA Hytec, Saab Seaeye and Seatronics.

Operators: Film-Ocean, Fugro, James Fisher Marine Services and ROVCO

Key facts

Inspection class ROVs are used to inspect the substructure, anchors, and mooring systems below the water line. They are also used to inspect the cable route, particularly in areas at risk of scour or other sea bed movements, and at other high-risk locations, such as crossings with other cables.

Inspection ROVs typically have a speed of 3 to 5 kn, weigh 8 to 12 kg and have dimensions 1 m x 0.7 m x 0.5 m.

They are equipped with propulsion systems, lighting, and a range of imaging equipment.

ROVs are launched from a DP2 vessel equipped with an A frame or moon pool. ROVs are attached to the vessel by umbilicals or tether cables which transmit electrical power, data, and optical signals. Tethers and umbilicals are usually strengthened with steel wire, to support the mechanical loads of the ROV underwater.

Radio waves don't travel far through water, so it's not possible to operate an ROV with wireless technology. There are acoustic and optical modem technologies that may someday enable wireless operation.

The continued development and use of unmanned subsea inspection vessels is an area of innovation.

What's in it

- Control system
- Lighting system
- Manipulator arm
- Power supply
- Propulsion system
- Remote camera

O.2.2.2.2 Autonomous underwater vehicle

Function

Autonomous underwater vehicles (AUVs) provide low cost means of surveying underwater, focussing on balance of plant assets such as cables and foundations.

Who supplies this

Manufacturers: ECA Hytec, General Dynamics, Teledyne Marine Gavia and Woods Hole Oceanographic Institution.

Operators: Fugro, Modus and UTEC.

Key facts

AUVs have the intelligence to operate independently from the vessel and has no connecting cables, whereas ROVs are connected to a remote operator.

AUVs have the potential to replace vessel-based surveys. They are launched offshore from parent vessels.

AUVs can be launched from a CTV and therefore avoid the need for a larger vessel with the lifting capacity needed to launch and recover an ROV.

What's in it

- Crew to operate and maintain it
- Vision system and specialist tools

O.2.2.3 Cable monitoring, inspection, and minor repair

Function

Identify faults in the array and export cables themselves, in addition to any cable accessories installed, and replace whole or sections of cable.

Who supplies this

Boskalis, Briggs Marine, CWind, Offshore Marine Management, Pharos Offshore and Power CSL.

Key facts

Cables are monitored and inspected to ensure they are operating as intended and to identify issues that could lead to future faults (see B.1 for further information).

Dynamic and static cables are monitored and inspected using mostly the same methods. The electrical performance of cables, joints and connectors is monitored using techniques including distributed acoustic and temperature sensing, and partial discharge monitoring. Surface or visual inspections are used to monitor the cable exteriors, cable accessories, cable protection system and cable entry/exit points from floating substructures, the sea bed and offshore substation foundations. Subsea visual inspections use ROVs.

The dynamic sections of array cables require additional visual inspection of the buoyancy and ballast elements and where it is tied down to enter the sea bed.

The frequency and number of units inspected depends on the results of the initial surveys, and are varied as results change for subsequent inspections. Surface surveys can be used to detect substantial cable exposure, but ROV surveys are required for more accurate burial depth data.

Cable damage may result from the mobility of dynamic sections in the water column, mechanical loads of wave and tidal action where the cable is exposed, from anchors or fishing gear, or as a result of handling during transport or installation that exceeds the cable's specification. Although cables typically come with a two-year warranty, none of the main causes of damage is covered by the warranty.

Excessive cable exposure or insufficient cable burial depth is typically resolved by remedial measures including protective mattresses and rock dumping, normally using a dynamically positioned fall pipe vessel, or occasionally side-dumping vessels. In the worst case, sections of cable may need to be reburied.

The owner is responsible for monitoring and surveying the cable and repairing it when required. The survey work and remedial work is likely to be subcontracted to a specialist provider.

- Array cables are always owned by the wind farm owner.
- Export cables are normally owned by the transmission system operator, or in the UK they are transferred to an offshore transmission system owner (OFTO) within the first 18 months after works completion date.

Some offshore wind farms have redundant export cables so a fault on one cable does not necessarily lead to loss of wind farm output.

Cable repair normally requires a full cable-laying spread consisting of a CLV with a cable plough or jetting equipment, with a quadrant to ensure that the minimum bend radius is not exceeded. On deck, the cable is cut, a new section inserted with cable joints linking the new and old sections, and any accessories are replaced. Unlike in subsea telecoms, where cables are largely standardised, subsea power cables may differ substantially. In the past, bespoke joints have been used but there is interest from transmission system operators in developing universal joints.

For array cables, shorter cable lengths and challenges in joining shorter cables mean that replacement of the cable may be more cost effective than repair. If so, the cable is cut or disconnected from each floating substructure, the array cable length removed, and a new cable laid using the same process as for its installation.

What's in it

- I.2.3 Cable-laying vessel
- Maintenance record management
- O.2.2.2.1 Remotely operated vehicle
- Rock dumping vessel

O.2.2.4 Scour monitoring and management

Function

Mitigates the risk of undermining sea bed movements on infrastructure installed below or on top of the sea bed, including at anchors and around the jacket foundation of the substation.

Who supplies this

Coda, Octopus, DHI, HR Wallingford, Norfolk Marine and Subsea Protection Systems.

Key facts

The presence of scour (erosion of the sea bed surface) around marine structures is common. Large diameter structures, like fixed monopile offshore wind turbine foundations, are particularly prone to scour because of the deflection of water movement around the structure.

Drag embedment anchors are buried under the sea bed (see B.3.1 for further information). They require monitoring to ensure they remain buried at sufficient depth. Suction and pile driven anchors protrude from the sea bed but are typically small diameter structures meaning that scour is unlikely to develop as quickly. The shallow embedded depths of drag embedment anchors means that any scour that does occur presents a bigger risk to the anchor's performance.

Scour is generally managed through rock (or grout, sand, or gravel) dumping. Mats are generally placed on top and these stabilise the infill material and prevent secondary scour. Frond mats, tyre-filled sacks and tyre-based mats have also been used.

Concrete mattresses may also be used, potentially with protective mats, where cables have become exposed.

What's in it

- Rock dumping
- Sea bed inspection
- Scour protection mats

O.2.2.5 Substation monitoring and maintenance

Function

Ensures there is no interruption to transmission from electrical failures or structural problems with the offshore platform.

Who supplies this

High voltage electrical contractors: ABB, GE Grid Solutions, Schneider Group and Siemens Power Transmission and Distribution.

Offshore contractors: Deutsche Windtechnik, Petrofac.

Key facts

Monitoring and maintenance of the offshore substation primarily consists of non-intrusive inspections of topside switchgear and transformers, sampling of transformer oil, foundation and topside structural inspection and resulting infrequent repair interventions (see B.4 for further information).

The owner carries out paint repairs and secondary steelwork repairs (for example to railings, gratings, gates, stairs, and ladders).

Serious repair operations, such as replacing transformers, require heavy lift vessels.

Rapid turnover parts and consumables are stored in a large warehouse at the onshore base.

Back-up diesel generators require periodic maintenance and refuelling.

Access to the substation may be by vessel or helicopter but since few failures require urgent attention, the weather downtime of vessels may not be as important a consideration as it is for turbines. During planned power outages to support detailed inspection and maintenance operations, careful planning is required to ensure weather windows are used to avoid excessive wind farm downtime if work cannot be completed and assets re-energised.

Onshore substation maintenance comprises non-intrusive inspections of switchgear, transformers, and any reactive power compensation equipment (see B.5 for further information). Infrequent repair in response may be required.

Unlike many of the systems of an offshore wind farm the onshore substation is almost entirely non-offshore wind specific, consisting of standard high-voltage electrical equipment.

What's in it

- Inspection
- Maintenance record management

O.2.3 Statutory inspections

Function

Statutory inspections (and other health and safety inspections) are a crucial activity to ensure the ongoing safe operation of wind farm infrastructure and systems, and to fulfil statutory obligations to inspect safety-critical systems on a regular basis.

What it costs

About £200,000 per annum for a 450 MW floating offshore wind farm.

Who supplies this

Bureau Veritas, DNV, SGS and TÜV SÜD

Key facts

Safety-critical items are subject to a statutory inspection regime, where there are legal requirements including recommended inspection frequencies and method of inspection. Inspections are carried out by qualified personnel, either as part of the primary turbine maintenance works or by a team of independent inspectors. Inspection frequencies are six-monthly or annual, depending on the equipment. If a scheduled inspection has not been carried out then technicians are not allowed to use the affected equipment, which may stop maintenance and repair activities from being carried out.

Most owners train their own technicians for these roles as they are frequent but require minimal time. Where there is a requirement for periodic statutory inspections and certification, such as for fall arrest systems, independent certifiers provide these services.

Owners seek to perform inspections prior to other planned work being carried out in the summer months to minimise the likelihood of weather delays and ensure equipment remains certified for use.

Safety-critical devices and equipment that require statutory inspections include:

- Anchor points
- Boat landing and ladders
- Davit cranes
- External gates and railings and floor gratings
- External evacuation and rescue equipment
- Fall arrest systems
- Firefighting equipment and fire prevention equipment
- First aid supplies & equipment
- Navigation aids and aviation lighting
- Pressure systems
- Turbine cranes

What's in it

- O.2.3.1 Health and safety equipment

O.2.3.1 Health and safety equipment

Function

Health and safety equipment provides personnel with access to vital equipment to reduce the risk of injury, and to provide equipment to assist in emergency situations.

Who supplies this

Aspli, Trauma Resus, Viking Life Saving Equipment and WFE Safety.

Key facts

A comprehensive set of health, safety and personal protection equipment is carried in the project vessels or stored in each turbine. Running stock is maintained at the onshore O&M logistics facilities.

Turbines have basic emergency equipment to permit overnight occupation in the turbine in the event of personnel being stranded due to access restrictions.

Typical health, safety and personal protection equipment includes:

- Advanced medical kits
- Ear defenders and safety eyewear
- Emergency communications devices
- Emergency rations and water
- Eye-washing kits
- First aid kits for minor injuries
- Fire extinguishers and suppressants
- Fuel and diesel spill kits
- Gloves and safety boots

- Rescue equipment including descenders, spinal boards and stretchers, hub rescue equipment, and
- Survival suits, personal locator beacon, life-vests, and floatation devices.

What's in it

- Inventory tracking

O.3 Major repair

Function

The major refurbishment, replacement, and repair of large components such as gearboxes, blades, transformers, generators, substructures, or substation components at the wind farm.

Who supplies this

Major repair in-situ will be supplied by marine contractors with suitable vessels. Major repair using tow-to-port requires AHVs, construction ports and large cranes.

Key facts

The major repair of large components is not a pre-planned activity in wind farm O&M. Incidents are rare but do occur when critical components have failed, are likely to fail imminently or present health and safety risks.

Major repair of large components at fixed offshore wind farms usually takes place on-site using jack-up vessels. This approach is not available for floating offshore wind farms as the water depths are likely to be too deep for jack-up vessels.

Major repair for floating offshore wind farms can be completed by either towing the assembled wind turbine to port and completing any work at the quayside, or in-situ using motion-compensated vessels. The technology required to facilitate floating to floating lifts for in-situ major repair is not currently available.

What's in it

- O.3.1 Main component refurbishment, replacement, and repair (in-situ)
- O.3.2 Main component refurbishment, replacement, and repair (tow-to-port)

BVGAssociates

O.3.1 Main component refurbishment, replacement, and repair (in-situ)

Function

The major refurbishment, replacement, and repair of large components such as gearboxes, blades, transformers, generators, substructures, or substations at the wind farm.

Who supplies this

Boskalis, Fred. Olsen, Heerema, James Fisher Marine Services, Maersk, Saipem, Seajacks, Subsea 7, TechnipFMC, Van Oord and Ziton.

Key facts

All but the shallowest floating offshore wind farms are located at sites too deep to use jack-up vessels for main component refurbishment, replacement, and repair at site.

Nevertheless, on-board turbine service cranes can lift substantial loads from the nacelle to the floating substructure level to exchange or repair some major parts.

Exchange is carried out in one visit, followed by off-site refurbishment. Retrofit programmes are carefully planned to ensure effective vessel utilisation taking into account repair turnaround times. This means that asset downtime, and hence lost revenue, is minimised, but requires the availability of spare components.

Any lift from the floating substructure to a vessel needs to be heave compensated as a minimum, and ideally 3-D motion compensated.

The technology to facilitate floating-floating lifts for the largest components, such as gearboxes, is not currently available. Conducting component replacement in-situ for these items, therefore, is not an option.

There are many innovations being progressed to address this challenge. In the future, in-situ refurbishment, replacement, and repair is expected to be a cost-effective option for the largest components.

What's in it

- Replacement parts
- SOVs with motion compensated crane
- Specialised lifting equipment

O.3.2 Main component refurbishment, replacement, and repair (tow-to-port)

Function

The major refurbishment, replacement, and repair of large components such as gearboxes, blades, transformers, generators, substructures, or substations at a port.

Who supplies this

AHVs: Boskalis, Bourbon Offshore, Damen, DOF Subsea, Maersk, MMA Offshore, Siem Offshore, SEACOR Marine, Solstaad Offshore and Vard Marine.

Construction ports in the UK: Aberdeen, Cromarty Firth and Dundee.

Jack-up cranes: DEME, Fred. Olsen, Jan de Nul, Seajacks, Seaway 7, and Van Oord.

Key facts

Conducting main component refurbishment, replacement and repair in-situ is challenging as motion-compensated lifting operations are required. Alternatively, floating offshore wind turbines can be towed to port for main component refurbishment, replacement, and repair to take place.

This involves disconnecting the floating offshore wind turbine from its moorings and cables and towing it to a port using AHVs. At the port, maintenance work can be undertaken using a jack-up vessel or a large land-based crane.

A tow-to-port strategy is less attractive than an in-situ strategy because turbine downtime is longer, resulting in larger revenue losses. It also requires floating offshore wind turbines to be towed to a construction port with the space, facilities and water depth required to repair floating offshore wind turbines. Alternatively, the floating offshore wind turbine could be towed to a sufficiently shallow, sheltered site where a jack-up crane vessel would be used.

Tow-to-port also requires floating offshore wind turbines to be disconnected and reconnected from cables and moorings.

Due to the unavailability of in-situ main component refurbishment, replacement, and repair, this is the only option currently available to floating offshore wind farm owners.

Retrofit programmes are carefully planned to ensure effective vessel utilisation, taking into account repair turnaround times. This means that asset downtime, and hence lost revenue, is minimised.

What's in it

- I.4.1 Anchor-handling vessel
- I.8 Construction port
- Jack-up vessel or land-based crane

O.4 Offshore vessels and logistics

Function

Offshore vessels are used to access offshore infrastructure, and offshore logistics involves management and coordination of all marine-based activities and operations.

What it costs

About £1 million per annum for a 450 MW floating offshore wind farm.

Who supplies this

James Fisher Marine Services, SeaRoc, Vissim and WindandWater.

The wind farm owner establishes and manages a marine operations centre at the main O&M port.

Key facts

Marine coordination involves the 24/7 monitoring of the locations of all vessels and personnel within the vicinity of the project, including the supply and interpretation of specialist tools such as marine coordination software.

Cameras are often located on selected offshore structures to enable CCTV feeds to review conditions and monitor offshore activities.

Operators need to make judgements about the priority of activities based on the scheduled maintenance and unscheduled service workload and weather forecast. The industry is increasingly adopting software simulation tools to maximise operational efficiency in relation to scheduling tasks and deploying resources, taking account of weather conditions, sea state, vessel capability and operational priorities.

Bigger wind farms further offshore and with more complex operational systems increase the logistical challenge.

Robust communication equipment and infrastructure is a key element of offshore logistics in order to ensure live communication between all personnel.

Small wind farms close to shore use CTVs to provide daily transport to the wind farm for technicians. Large wind farms further from shore use SOVs to house technicians offshore for multiple weeks at a time to conduct maintenance campaigns.

Some portfolios leverage benefits of scale by using SOVs to service several smaller wind farms in the same geographical region.

What's in it

- O.4.1 Crew transfer vessels
- O.4.2 Service operation vessels
- O.4.3 Turbine access systems
- O.4.4 Helicopters

O.4.1 Crew transfer vessels

Function

Crew transfer vessels (CTVs) provide access for technicians and contractors to the wind turbines from the onshore O&M base to turbine locations and substation. CTVs are the preferred access solution for projects closer to shore.

Figure 45 A crew transfer vessel servicing the WindFloat Atlantic floating offshore wind farm. *Photo of the WindFloat Atlantic project courtesy of Principle Power/Ocean Winds.*

What it costs

The charter day rate for a CTV is about £2,000 (excluding fuel), depending on specification, availability, and contract period.

Who supplies this

Manufacturers: Alicat, Fjellstrand, Manor Renewables, South Boats and Umoe.

Vessel operators: Acta Marine Wind Services, MPI Workboats, Northern Offshore Services, Turbine Transfers and Windcat Workboats.

Key facts

CTVs transport personnel to the wind farm on a daily basis and do not have overnight facilities.

Key requirements are robust vessels that can operate in adverse weather conditions. Wind farm operators typically use aluminium catamarans up to 30 m long with capacity for 12 to 16 technicians.

CTVs are typically Class I passenger ships, as classified by the Maritime and Coastguard Agency, which enable them to work further than 60 nm from a safe haven. These vessels can be built to carry up to 24 passengers. Vessel speeds can be up to 30 kn and vessels are designed to transfer maintenance team members in comfort and safety to the wind farm ready to start work.

There is an oversupply of small CTVs (less than 20 m), with operators typically opting for larger vessels with longer ranges and better sea keeping.

There is interest in SWATH (small waterplane area, twin hull) and SWASH (small waterplane area, single hull) type vessels to increase technician comfort and lower weather downtime.

CTVs may have fixed or controlled pitch propellers but operators may prefer the increased manoeuvrability of water jets. Vessels with a smaller draught (less than

2 m) may be used where harbours are more challenging to operate from due to water depths.

CTVs have a load capacity up to 30 t for turbine components and consumables, as equipment. Fuel is not typically included in the charter cost and there is an important emphasis on fuel efficiency of vessels.

What's in it

- Crew
- Technicians

O.4.2 Service operation vessels

Function

Service operation vessels (SOVs) provide an offshore O&M base, with staff working from the vessel for periods of two to four weeks at sea. SOVs are the preferred way to maintain wind farms located far from shore.

Figure 46 Fleet of service operation vessels servicing a fixed offshore wind farm. ***Image courtesy of North Star Renewables. All rights reserved.***

What it costs

The charter day rate for an SOV is about £30,000 per day depending on size and fit out (excluding fuel).

Who supplies this

Manufacturers: Astilleros Gondanm Cemre, Damen, Royal IHC and Ulstein.

Vessel operators: Acta Marine, Bernard Schulte, Bibby Marine, Esvagt, Louis Dreyfus Travocean, Østensjø Rederi and Vroon.

Key facts

SOVs offer accommodation, mess, and welfare facilities for wind farm technician staff, as well as workshop and spares storage. SOVs stay at the wind farm for up to four weeks at a time, at which point they return to home port to restock and change crews.

Access to the wind turbines is achieved either by smaller CTV, daughter craft, by helicopter, or directly from the SOV using a turbine access system.

SOVs have operational speeds of up to 15 kn. They are equipped with dynamic positions systems. Vessel manoeuvrability is a key requirement to reduce positioning time and therefore costs. For this reason, there is little use of surplus platform support vessels (PSVs) from the oil and gas industry. PSVs have a more important role in supporting installation and commissioning.

SOVs can typically accommodate a crew between 50 and 100, of which up to 50 may be wind farm workers.

What's in it

- Accommodation berths
- Mess, welfare, and leisure facilities
- Motion-compensated crane
- Spares and tooling storage
- Walk to work system
- Workshop facilities

O.4.3 Turbine access systems

Function

Turbine access systems provide access to the turbine from a CTV or SOV. Systems are designed to permit access to the turbines in as wide a range of sea-states as possible, in the interests of maximising possible maintenance time and turbine availability.

What it costs

Costs typically included in vessel costs.

Who supplies this

Ampelmann, Fjellstrand, Houlder, Osbit, Uptime and Windcat Workboats.

Key facts

Many SOV turbine access systems are based on motion-compensated gangways that react in real time to changes in the sea surface, providing a stable platform to allow personnel to walk from the vessel onto the turbine. Motion compensating gangways have been trialled on CTVs.

Such systems are designed within operational limits and do not permit access in the most severe sea states.

What's in it

- Control systems
- Hydraulics
- Steel infrastructure

O.4.4 Helicopters

Function

Helicopters are used to provide access for technicians and contractors to the wind turbines and offshore substation.

What it costs

About £200,000 per annum for a 450 MW floating offshore wind farm. This is dependent on the level of expected use (such as flying hours and helicopter type) defined by the operational strategy.

Who supplies this

Manufacturers: Airbus, Leonardo, and Sikorsky.

Operators: Babcock, Bond Aviation Group, Heli Service International and Northern Helicopter.

Key facts

Helicopters allow access in otherwise inaccessible sea state conditions. Their high speeds and low carrying capacities fit well with the dispersed nature of offshore wind projects and the high frequency of low effort interventions that make up a large proportion of offshore visits.

The high costs mean that helicopters are not used as primary means of technician transport. They can be cost-effective for projects at the limit of the effective range of CTVs for which the fixed cost of SOVs is unattractive.

Arrangements to use local airports need to be developed or a dedicated helicopter base set up at the operations port. This usually requires additional planning consent. It is important to locate the helicopter close to the operations base to reduce inefficiencies in journey time.

Helicopters rarely land on the offshore installations, with technicians being winched down to the turbine. Helicopters are limited by weight restrictions and typically carry two to six technicians depending on the type of helicopter. The type of spare parts and tools that can be carried is limited by weight and size.

Helicopters are normally contracted on a long-term basis, with either exclusive or shared access to the aircraft.

What's in it

- Specialist offshore pilot training

O.5 O&M port

Function

O&M ports provide facilities from which long-term O&M activities are carried out – such as jetties or quaysides for CTVs and SOVs, warehouses, workshops, and offices – and which support major repairs.

Figure 47 The Port of Peterhead which is being used as the operations and maintenance port for the Hywind Scotland project. ***Image of Peterhead Port courtesy of Camtech Engineering. All rights reserved.***

What it costs

About £180,000 per annum for a 450 MW floating offshore wind farm.

Who supplies this

Any port with the necessary facilities, located within a suitable distance of the floating offshore wind farm, could become an O&M port. Aberdeen and Peterhead are the first in the UK used to support floating offshore wind farms, which service Kincardine and Hywind Scotland respectively.

There are expected to be a smaller number of major repair ports as these have more specific requirements. The Port of Nigg, for example, has suitable facilities and is well-located to support floating ScotWind projects.

Key facts

O&M ports for floating offshore wind farms are expected to be similar to those for fixed, whether using CTVs or SOVs.

Typically, wind farm owners look to use the nearest port that meets its specifications to minimise transfer times and reduce the risk of time being lost due to bad weather. Nevertheless, owners typically competitively tender the contract for the provision of port services. For wind farms further from shore, the use of offshore accommodation and other facilities (possibly shared with other wind farms) becomes more attractive.

Port location is critical. Far from shore port requirements differ from a wind farm that is operated using CTVs and workboats only.

Tow-to-port maintenance almost always requires a different port as ballasted semi-submersible floating substructures have drafts of 15 to 20 m. A construction base port for floating offshore wind projects could have the depth requirements and facilities to do this work, such as quaysides and cranes (see I.8 for further information).

If suitable O&M ports are not available for floating offshore wind, floating offshore wind turbines need to be moored in storage areas outside of the O&M port and serviced using a jack-up crane vessel.

Safe means of transfer onto vessels is needed. This often requires the installation of pontoons to ensure a level access route in all tidal conditions.

Each support vessel needs a berth of up to 30 m. A 450 MW wind farm may require the operation of two or three vessels, depending on the distance from the wind farm to shore and the maintenance strategies chosen, although up to five berths may be specified in order to provide capacity for peak periods. Uninterrupted access requires the availability of a non-drying harbour with minimal tidal restrictions.

O&M port facilities required include:

- Jetties for CTVs, with approximately 35 m per CTV, depending on the size of CTV used, and a minimum draft of 3 m, often with 2 t SWL telescopic boom jetty cranes
- Quaysides for SOVs, with approximately 100 m quayside per SOV and minimum draft of 7 to 8 m.
- Warehouses for spare parts
- Workshops for work such as sorting equipment brought back from site, kitting of parts and equipment to go to site, and minor refurbishment
- Office buildings to house the operations control centre and other project operations staff, and
- Convenient access for O&M technicians.

Ideally all ports would be as close as possible to the floating offshore wind farm. In practice they are generally:

- O&M ports using CTVs: generally, within 40 km.
- O&M ports using SOVs: generally, within 200 km.
- Repair ports: could be a long way from the wind farm site but are expected to be used infrequently.

What’s in it

- Jetties
- Operations office
- Parking
- Quaysides
- Warehouses
- Wet storage, for floating offshore wind turbines being repaired
- Workshops

D Decommissioning

Function

Removal or making safe of the infrastructure of a floating offshore wind farm at the end of its useful life, plus disposal of equipment.

What it costs

About £66 million for a 450 MW floating offshore wind farm (gross, excluding any resale value of equipment removed).

Who supplies this

Contractors will be similar to those used for installation.

It is likely that other offshore operators will also enter the space, including firms with offshore oil and gas decommissioning experience.

Key facts

At the end of the initial design life of a floating offshore wind farm, there are a number of options:

- Extend the operational life of existing assets through a programme of risk assessments, inspections, addressing regulatory aspects, and component replacement.
- Repower the site with new turbines, which are expected to be larger. This requires decommissioning the existing floating offshore wind turbines, mooring lines, and array cables. It could be possible to extend the life of electrical transmission assets.
- Fully decommission the site.

Properly financed decommissioning plans typically are required as part of planning approval to construct the floating offshore wind farm. In practice, permission is likely to be sought to deviate from decommissioning plans as the sector's decommissioning techniques mature. The UK Government acts as decommissioner of last resort.

Decommissioning of installed floating offshore wind turbines will require complete removal of the floating offshore wind turbine and its mooring system. The process for decommissioning anchors depends on the technology adopted and its sea bed connection.

For nacelle components, towers, and steel floating substructures the potential for recycling is considerable. There is no established process for recycling composite materials such as those used in the blades. Several manufacturers are developing new composite materials and processes to enable blade materials to be reused.

Careful planning is needed to ensure that hazardous materials, such as the oil used in transformers, are not spilled.

Environmental surveys will typically be required before and after decommissioning, along with post-decommissioning management of the site in line with the Energy Act 2004.

What's in it

- D.1 Floating offshore wind turbine decommissioning
- D.2 Anchor and mooring system decommissioning
- D.3 Cable decommissioning
- D.4 Offshore substation decommissioning
- D.5 Decommissioning port
- D.6 Reuse, recycling, or disposal

D.1 Floating offshore wind turbine decommissioning

Function

Disconnection of floating offshore wind turbine from moorings and cables at the wind farm site and tow back-to-port. It includes disassembly into smaller assemblies or components for reuse, recycling, or disposal.

What it costs

About £3 million for a 450 MW floating offshore wind farm.

Who supplies this

Expected to be the same as the floating offshore wind turbine installers.

Key facts

The floating offshore wind turbine decommissioning process is the reverse, at a high-level, of the installation process. The floating offshore wind turbine is disconnected from mooring lines and cables at the site. It is then towed back to the port using AHVs and smaller support vessels, for wind turbine and floating substructure disassembly.

Where it is determined that the remaining life is sufficient, there will be a market for reuse of second-hand components, either as spares or re-installation elsewhere, for example yaw motors or anemometers.

In general, the removal process will be quicker than for installation because minor damage to components will be less critical. If components are to be recycled rather than reused, then less care needs to be taken to preserve the delicate aerodynamic surfaces and the condition of components. This may enable the use of different equipment or operations in a wider range of operating conditions.

What's in it

- I.6 Floating offshore wind turbine installation

D.2 Anchor and mooring system decommissioning

Function

Removal and shipment to shore of anchors and mooring systems.

What it costs

About £18 million for a 450 MW floating offshore wind farm.

Who supplies this

Expected to be the same as the anchor and mooring installers.

Key facts

Decommissioning plans may define specific requirements for removal of components below the mud line which may drive the choice or design of anchors and installation methods.

The removal process is likely to involve the use of a work-class ROV fitted with a vision system and a range of cutting and drilling tools. These include guillotine saws, hydraulic hole cutting tools (for making lifting holes) and abrasive waterjet cutting.

Mooring lines are disconnected from the floating substructure, then disconnected from anchors, then brought onto the deck of an AHV (see I.4 for further information). Where the connection to the anchor is not accessible, the mooring line may be cut. As they are brought on board any buoyancy modules, clump weights and load-reduction devices are removed.

The removal of anchors depends on their type and the commitments made in the decommissioning plan:

- Drag embedment anchors are relatively easy to remove, with several different techniques being used. These vary according to the design of the anchor but include pulling the anchor upwards and in the opposite direction to its operational loading.
- Suction-embedment anchors are also relatively easy to remove. A high-pressure line is connected to the anchor using an ROV and water is pumped into the anchor to reverse the embedment process.
- Piled anchors are most likely to cut off at an agreed height, or the pile driven under the sea bed and left in position. Initially, the process is likely to draw on the fixed offshore industry's experience of decommissioning monopile structures.

What's in it

- I.4.1 Anchor-handling vessel
- O.2.2.2.1 Remotely operated vehicle

D.3 Cable decommissioning

Function

Removal and shipment to shore of cables.

What it costs

About £33 million for a 450 MW floating offshore wind farm.

Who supplies this

Expected to be the same as the cable installers.

In addition, companies such as CRS Holland, Pharos Offshore and Subsea Environmental Services can carry out subsea cable recovery.

Key facts

The value, especially of the main conductor material in array and export cables, is such that it is likely to cost effective to remove the cables.

There will be no significant differences in the process of decommissioning subsea cables for floating offshore wind farms compared to fixed offshore wind farms.

Cables will be disconnected at each end. They are then pulled from the sea bed and wound on to drums or cut into short sections for storage on the decommissioning vessel. Cable accessories, including any buoyancy modules or cable protection installed, will be removed with the cable. The method of gripping and pulling the cable will depend on how the cable is fixed to the sea bed, the ground conditions and burial depth (if buried). For buried cables in sandy conditions the approach is likely to involve fluidising the sea bed while the cable is pulled. The industry is likely to develop new tools for the process.

Particular care is needed at cable crossings with other power or telecommunications cables to avoid damage to functioning assets.

What's in it

- I.2 Offshore cable installation

D.4 Offshore substation decommissioning

Function

Removal of the offshore substation and its substructure to shore.

What it costs

About £12 million for a 450 MW floating offshore wind farm.

Who supplies this

Likely to be the same as the offshore substation installers.

Key facts

Decommissioning plans may define specific requirements for removal of components below the mud line which may then drive the choice or design of offshore substation foundation or floating substructure, and installation methods.

The process is likely to be a reverse of the installation process. Fixed offshore substations will be dismantled using a large vessel. It may prove cheaper to cut the structure into sections to enable a series of smaller lifts that can be undertaken by a lower cost vessel. Floating offshore substations will be towed back to port for decommissioning.

In some cases, there will be a market for reuse of refurbished electrical components.

If the remaining life of the substation, after refurbishment, is sufficient, the substation could be left in-situ and reused for a repowered wind farm of the same capacity.

What's in it

- I.1 Offshore substation installation

D.5 Decommissioning port

Function

The port where equipment removed is offloaded and marshalled for the next stage of its processing.

What it costs

Included in decommissioning contract for each of the components.

Who supplies this

Similar to construction ports for floating offshore wind, but also including facilities with a lower specification and locations dedicated to decommissioning.

Examples in the UK include Aberdeen, Cromarty Firth and Dundee, and specialist decommissioning facilities at Seaton.

Non-UK ports include Ferrol (ES), Nouvelle (FR) and Rotterdam (NL).

Key facts

Facilities similar to those used for installation will be required. Large structures to be broken up are likely to be transported to facilities dedicated to such activity.

Ideally, decommissioning ports will have salvage and processing facilities on site. Some ports may develop expertise in handling certain types of materials. Some specialisations developed as part of oil and gas decommissioning may be valuable, even if this involves additional transit time from the floating offshore wind farm site.

What's in it

- I.8 Construction port

D.6 Reuse, recycling, or disposal

Function

Once equipment is onshore, there is a motivation to extract maximum value via reuse, recycling, or disposal.

What it costs

Overall, likely to be a net positive value.

Who supplies this

Delta Marine, DUC Marine Group and Scaldis Salvage & Marine.

Key facts

Currently, different parts of decommissioned onshore wind turbines are reused, recycled, or disposed of, depending on age, condition and material content. There is an established second-hand market for onshore turbines known to be robust and reliable with sufficient fatigue life remaining. The turbines are refurbished and installed on new foundations for operation up to 50% beyond the design life.

Offshore costs and financing mean it is unlikely that offshore turbines will be decommissioned with sufficient fatigue life remaining to be re-installed offshore. Turbines are typically disassembled for recyclable scrap. The majority of nacelle and tower mass has residual value and only small amounts of turbine mass requires disposal. Turbines contain a range of valuable materials including steel, cast iron, copper, aluminium and in the future, permanent magnet materials.

Today, most composite blades cannot be cost-effectively recycled. It is likely that new materials and methods will emerge by the time floating offshore wind turbines are deployed at large scale, as there are a range of projects underway in this area.

Blades are typically made from a combination of glass and carbon-fibre in epoxy- or polyester-based resin matrices, along with polyethylene terephthalate (PET) foam or balsa filler. At the root end, there are steel inserts to provide bolted connection to the blade bearing. There is also typically a copper-based lightning protection system.

So far, blades have been cut up and either sent for burning (in waste to energy or district heating plant), to landfill or for low-grade re-use. The first more easily recyclable blades are however now in use offshore.

Most steel floating substructures, anchors, moorings, substation topsides and substation foundations have high steel content. This can be broken down and recycled as input to the manufacture of new steel components. Synthetic rope used in mooring lines can also be used for other applications. Some substation components may be reused. Others can be recycled, again with relatively low proportion having no residual value and requiring safe disposal.

Concrete floating substructures can be broken down and the aggregate used in other concrete construction.

The cable conductor can be readily processed and reused in a range of sectors. XLPE insulation may be cleaned, dried and ground, and recycled as filler for new power cables or as insulation in lower voltage cables or accessories.

Glossary

Table 3 Glossary of floating offshore wind terms.

Term	Definition
Anchor	Structures embedded into the sea bed that resist the loads from the mooring lines or a floating substructure, or the tendons of a tension leg platform.
Annual energy production (AEP)	The amount of energy generated in a year. Gross AEP is the predicted annual energy production based on the turbine power curve, excluding losses. Net AEP is the metered annual energy production at the offshore substation, so includes wind farm downtime, wake, electrical and other losses.
Array cable	Electrical cable that connects the turbines to each other and the offshore substation.
Assembly (pre-assembly and final assembly)	Pre-assembly: the assembly of components to form major sub-assemblies, such as the pre-assembly of tower sections into a tower. Final assembly: the assembly of major subassemblies with the floating substructure, to form an assembled floating offshore wind turbine.
Availability	The percentage of time the assets are available to produce / transfer power if the wind speed is within the operational range of the turbine.

Term	Definition
Balance of plant (BoP)	Includes all the components of the wind farm except the turbines, including transmission assets built as a direct result of the wind farm.
Barge	A major type of floating substructure. It has a single hull that pierces the waterline and may be ballasted to provide additional stability.
Department for Business, Energy, and Industrial Strategy (BEIS)	UK government department that is responsible for business, industrial strategy, science and innovation and energy and climate change policy.
Consent	Planning permission.
Cable protection system (CPS)	Cable protection systems protect the subsea cable against various external aggressions. Systems include bend restrictors and bend stiffeners where the cable may be subject to increased loading.
Capacity factor	Ratio of annual energy production to maximum energy production if the turbine / wind farm ran at rated power all year.
Capital expenditure (CAPEX)	Spend on all activities up until works completion date.
Catenary	A type of curve, its shape results from the force of gravity acting on the self-weight of a flexible line between two supported end points. Examples include a mooring chain or a dynamic array cable.

Term	Definition
Contract for difference (CfD)	Contract where government agrees to pay the wind farm owner the difference between an agreed strike price and the average market price of electricity (reference price). If the difference is negative the wind farm owner pays the difference to the government.
Crew transfer vessel (CTV)	A vessel used to transport wind farm technicians and other personnel to the offshore wind farm turbines either from port or from a fixed or floating base. Vessels operating today are typically specially designed catamarans that accommodate around 12 passengers.
Cross-linked polyethylene (XLPE)	A thermoset material widely used as electrical insulation in power cables.
Decommissioning expenditure (DECEX)	Spend on removal or making safe of floating offshore infrastructure at the end of its useful life, plus disposal of equipment.
Dynamic cable	The section of a cable, whether array or export, that is suspended from a floating substructure and hangs in the water column. The floating end moves (hence the term dynamic) relative to the end that is attached to the sea bed, due to various loads on the substructure and the suspended cable.
Environmental impact assessment (EIA)	Assessment of the potential impact of the proposed development on the physical, biological, and human environment during construction, operation and decommissioning.

Term	Definition
Engineer, procure, construct, and install (EPCI)	A common form of contracting for offshore construction. The contractor takes responsibility for a wide scope and delivers via own and subcontract resources.
Export cable	Electrical cable that connects the onshore and offshore substations, or between an AC offshore substation and a DC converter substation.
Front end engineering and design (FEED)	Front-end engineering and design (FEED) studies address areas of wind farm system design and develop the concept of the wind farm in advance of procurement, contracting and construction.
Final investment decision (FID)	The point at which a developer has in place all the consents, agreements and major contracts required to commence project construction (or these are near execution form) and there is a firm commitment from equity holders and debt funders to provide funding to cover the majority of construction costs.
Floating offshore wind farm	A wind farm that uses floating offshore wind turbines.
Floating offshore wind turbine	The integrated wind turbine and floating substructure. The same term is used whether it is in a port or connected via its mooring system at the wind farm site.
Floating substructure	A buoyant substructure for turbines, or offshore substations, anchored to the sea bed via mooring lines. The term includes several substructure types including spar buoy, barge, tension leg platform and semi-submersible.

Term	Definition
Gas insulated switchgear (GIS)	Gas-insulated switchgear is often chosen for its compactness and increased reliability over air insulated switchgear but has higher cost.
Gigawatt (GW) and Gigawatt hour (GWh)	Unit of power and unit of energy.
High voltage alternating current (HVAC)	An electric power transmission system that uses alternating current for the bulk transmission of electrical power. Alternating current is the form in which electric power is generated by wind turbines and delivered to an end user.
High voltage direct current (HVDC)	An electric power transmission system that uses direct current for the bulk transmission of electrical power. For long-distance transmission, HVDC systems may offer lifetime cost advantages over HVAC systems over long transmission distances. They are currently only used for point-to-point connections.
Horizontal directional drilling (HDD)	Horizontal directional drilling is a low impact (trenchless) method of installing underground cables using a surface-launched drilling rig.
Jacket foundation	A major type of fixed foundation used for offshore substations and wind turbines. It consists of a small number of legs which support the major loads, connected to each other by braces to prevent buckling.

Term	Definition
Jewellery	The collective term for equipment attached to a mooring line, including: floatation elements, clump masses, shackles, H-links and load reduction devices.
Levelised cost of energy (LCOE)	Levelised cost of energy is a commonly used measure of the cost of electricity production. It is defined as the revenue required (from whatever source) to earn a rate of return on investment equal to the WACC over the life of the wind farm. Tax and inflation are not modelled.
Mean high water springs (MHWS)	The average tidal height throughout the year of two successive high waters during those periods of 24 hours when the range of the tide is at its greatest.
Mean sea level (MSL)	The average tidal height over a long period of time.
Megawatt (MW) and Megawatt hour (MWh)	Unit of power and unit of energy.
Monopile foundation	A type of foundation with a cylindrical tube (normally steel) that is normally driven tens of metres into the sea bed, although it can also be inserted into pre-drilled holes.
Mooring line	The line used to connect a floating substructure to an anchor. It can be made from steel chain, steel wire rope, or synthetic fibre rope.
Offshore substation (OSS)	The structure used to transform and transfer the energy collected by the wind turbines to land in the most efficient manner. It may involve increasing the voltage,

Term	Definition
	providing reactive compensation, and converting the current from AC to DC. Some wind farms may have more than one offshore substation and equipment may be located on a number of smaller structures and potentially on one or more turbine transition pieces.
Offshore Transmission Owner (OFTO)	An OFTO, appointed in UK by Ofgem (Office of Gas and Electricity Markets), has ownership and responsibility for the transmission assets of an offshore wind farm.
Operational expenditure (OPEX)	Spend on all activities from work completion date until decommissioning.
Operations and maintenance (O&M)	O&M comprises wind farm O&M and onshore transmission O&M. Definitions of O and M are as follows: Operations: day-to-day management including all the work not covered under maintenance and service. For wind farm O&M, this includes cost for port facilities, buildings, management personnel, environmental monitoring and community engagement. Maintenance of assets: scheduled (that is, planned a long time in advance) maintenance, that may be based on suppliers' recommendations or owner's experience. It includes condition-based or time-based maintenance programmes and planned health and safety inspections.

Term	Definition
	Typical maintenance includes inspection, checking of bolted joints and replacement of wear parts (with design life less than the design life of the project). Maintenance also includes the unscheduled interventions in response to events or failures. Interventions may be proactive (before failure occurs, for example responding to inspections or condition monitoring or reactive (after failure that affects generation has occurred). Also included are interventions due to major components not lasting the full turbine design life (even if intervention was planned prior to construction) and both on site repair and replacement of large and small components.
Ports	Manufacturing port: where equipment is made and shipped from, such as turbines or balance of plant. Construction port: where equipment is stored and pre-assembled, then finally assembled, before transport to site. O&M port: the base port for operations and maintenance vessels and supporting materials. Major repair port: a port which can accommodate major repairs of floating offshore wind turbines.
Remotely operated vehicle (ROV)	ROVs are remotely guided subsea mobile devices. They are usually deployed from a vessel. ROVs can be used for inspections or to carry out handling and repair.

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Term	Definition
Self-propelled modular transporter (SPMT)	SPMTs are remotely operated flatbed haulers used to transport large and heavy objects around ports and construction sites.
Semi-submersible	A major type of floating substructure. It has a large structure comprised of several buoyant columns or turrets that are connected using pontoons and/or trusses. It is typically ballasted to provide additional stability.
Service operation vessel (SOV)	A vessel that provides accommodation, workshops, and equipment for the transfer of personnel to turbine during O&M. Vessels in service today are typically up to 85m long with accommodation for about 60 people.
Significant wave height (Hs)	The wave height (trough to crest) of the highest third of the waves over a given period.
Spar	A major type of floating substructure. It consists of a tall cylinder housing dense ballast in its lower part and has a large draft.
Supervisory Control and Data Acquisition (SCADA) system	Data acquisition, transmission and storage system covering all wind farm assets. The SCADA system enable individual wind turbines, the wind farm substations and associated wind farm equipment to communicate operational status including faults. This allows operators to remotely diagnose faults and issue commands to stop, start and reset turbines and other equipment. The SCADA system keeps a full operating history of the wind farm.

Term	Definition
Tension leg platform (TLP)	A major type of floating substructure. It is relatively small compared to other types of floating substructure and its stability is provided by vertical, or predominantly vertical, tendons.
Transition piece	A part of the platform that provides the connection between the platform and the wind turbine tower. For floating substructures, it is usually an integral part of the platform.
Turbine rated power	The nominal maximum power output from a wind turbine. Sometimes this is referred to as capacity. The wind turbine is limited to this power output, which typically applies when the wind speed at the hub height exceeds about 12m/s and continues until about 25-30m/s when the wind turbine stops generating to avoid excessive loading. In more benign operating conditions characterised by ambient temperature, main component temperatures, wind speed, turbulence level and grid voltage levels, the output may be allowed to exceed the rated power by about 5%.
Unexploded ordnance (UXO)	Explosive weapons that did not explode when they were released and remain a risk to seabed users.
Weighted average cost of capital (WACC)	The weighted average rate of return a wind farm owner expects to compensate itself and its internal and external investors over the life of a project.
Wind shear	The degree to which wind speed changes with height.

Term	Definition
Works completion date (WCD)	Date at which construction works are deemed to be complete and the wind farm is handed to the operations team. In reality, this may take place over a period of time.

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About BVG Associates

BVG Associates is an independent renewable energy consultancy focussing on wind, wave and tidal, and energy systems. Our clients choose us when they want to do new things, think in new ways and solve tough problems. Our expertise covers the business, economics and technology of renewable energy generation systems. We're dedicated to helping our clients establish renewable energy generation as a major, responsible and cost-effective part of a sustainable global energy mix. Our knowledge, hands-on experience and industry understanding enables us to deliver you excellence in guiding your business and technologies to meet market needs.

BVG Associates was formed in 2006 at the start of the offshore wind industry.

We have a global client base, including customers of all sizes in Europe, North America, South America, Asia and Australia.

Our highly experienced team has an average of over 10 years' experience in renewable energy.

Most of our work is advising private clients investing in manufacturing, technology and renewable energy projects.

We've also published many landmark reports on the future of the industry, cost of energy and supply chain.