Floating Offshore Wind: Market and Technology Review

Prepared for the Scottish Government

June 2015

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List of abbreviations

Abbreviation	Meaning
ADEME	French Environment and Energy Management Agency
BOS	Balance of System
CAPEX	Capital Expenditure
CfD	Contract for Difference
DECC	Department for Energy and Climate Change (UK)
ETI	Energy Technologies Institute
FEED	Front End Engineering and Design
HAWT	Horizontal Axis Wind Turbine
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
LCOE	Levelised cost of energy
Met-ocean conditions	Meteorological and ocean conditions
O&M	Operations and maintenance
OPEX	Operational Expenditure
OWA	Offshore Wind Accelerator
R&D	Research and Development
RD&D	Research, Development, and Demonstration
ROC	Renewable Obligation Certificate
Semi-sub	Semi-submersible platform
TLP	Tension leg platform
TRL	Technology Readiness Level
VAWT	Vertical Axis Wind Turbine

Executive Summary

Offshore wind has been identified as one of the leading technology options to decarbonise the UK's energy system, with deployment expected to reach 20-55 GW by 2050, depending on the UK's broader energy mix and carbon reduction strategy (ETI, 2015). The UK is the current market leader in offshore wind power, with ~5 GW of installed capacity, all of which consists of conventional fixed-bottom foundation technology located in relatively shallow water depths (<40m) and near to shore (<30km). As installed capacity increases and the low-hanging fruit of shallow near-shore sites is exhausted, projects will need to be developed further from shore and in deeper water, which will pose greater technical challenges and constrain efforts to reduce costs. In response to this challenge, momentum is building around the potential for floating offshore wind foundation technology to unlock near-shore deep water sites at a lower cost of energy than far-shore fixed-bottom locations. Floating wind is particularly well suited to Scotland. A combination of high wind speeds, abundant near-shore deep water sites, and the ability to leverage existing infrastructure and supply chain capabilities from the offshore oil and gas industry create the requisite conditions to position Scotland as a world leader in floating wind technology.

This study has been commissioned by the Scottish Government in order to understand the current state of the floating wind industry and the key technical barriers that need to be addressed to make floating wind a commercial reality. The report presents a consolidation of the existing literature on floating wind. It provides a comprehensive overview of the technology and the range of concepts currently under development and examines the government support for floating wind, including the current pipeline of demonstration projects. The report also assesses the cost competitiveness of floating wind and provides a market outlook based on current trends. The study then takes a deep-dive into floating wind technology, providing a quantitative comparison between different concept typologies across a range of metrics, including cost, as well as mapping the technology readiness of floating wind concepts and highlighting what needs to be done to commercialise the technology. The outputs of this analysis inform a set of recommendations to the Scottish Government on how to best support the floating wind industry going forward. High-level details of the key findings are outlined below.

Market

According to the ETI (2015), offshore wind deployment could reach 20-55 GW by 2050. At the lower end of this projection it is expected that the more mature fixed-bottom technology will dominate, exploiting relatively shallow and near-shore sites that can be developed at lowest cost. Beyond ~20 GW, fixed-bottom offshore wind farms will be forced to move further from shore to access suitably shallow waters, which creates challenges for electrical transmission, particularly if high voltage DC connection is required. Far-shore sites also pose additional challenges for installation, O&M, and higher foundation costs moving into deeper water. This is particularly evident in Scotland, where existing projects are already being developed in water depths >40m and in complex seabed conditions. Floating offshore wind would circumvent a number of these challenges, unlocking deep water sites close to shore which would support conventional high voltage AC transmission, port-based O&M strategies, and lower installation and major repair costs by removing the need for expensive heavy-lift installation vessels. If offshore wind deployment reaches 40 GW, the ETI expect that 8-16 GW of this could be provided by floating wind technology, the majority of which would be based in Scottish waters. There is also enormous potential for floating wind in emerging offshore wind markets in Japan, the United States, and elsewhere in Europe, particularly in the Mediterranean and along the Atlantic coastline.

Despite the promise, floating wind technology is still nascent and has yet to be demonstrated at large scale. The challenge for the industry is to reduce costs from today's expensive demonstrators to a commercial model where designs can be optimised and the industry can benefit from the economies of scale needed to drive costs down. A number of cost projections suggest that floating wind can reach cost parity with fixed-bottom during the 2020s if adequate support is provided by government. This is reinforced by the results of this study, which suggest that leading floating wind concepts could attain a levelised cost of energy of £85-95/MWh in large-scale commercial projects, with further cost reduction possible over time[1]. However, there is a critical need to demonstrate this cost reduction potential, beginning with prototype and pre-commercial projects over the next few years, preparing the ground for commercial deployments beyond 2020.

Of the 30+ concepts currently under development, only five have been demonstrated at full scale (>1 MW) in an offshore environment. Having taken the lead in Europe with the world's first floating wind demonstrations in Norway in 2009 and Portugal in 2011, Japan has since invested heavily in floating wind technology, launching three floating concepts, including the world's first floating substation, with more demonstrations in the pipeline. The United States are also on track to install a pre-commercial array off the Pacific west coast and Europe has a growing pipeline of its own, particularly in France, Portugal, and Scotland, where developers are racing to commission their projects in time to qualify for the enhanced 3.5 ROCs for floating wind, which is set to expire in October 2018. Without a successor to this support mechanism there is a risk that Scotland may miss out on the opportunity to take a world leading role in floating wind technology.

Opportunity for Scotland

Scotland is an attractive market for floating wind development, combining excellent natural resources with an established supply chain and suitable port infrastructure developed for the offshore oil and gas sector that can be leveraged to service the floating wind industry. While fixed-bottom projects are constrained by deep waters and challenging seabed conditions, floating wind concepts are largely decoupled from the seabed and are well-suited to many of the deep water locations surrounding Scotland, which are blessed with consistent high wind speeds. There are also several technology synergies with the oil and gas industry, which successfully introduced floating platforms to access oil and gas reserves in deep water locations at a lower cost than fixed-bottom alternatives. As such, there is a great deal of overlap regarding the design, fabrication, and installation of the platform, moorings, and anchors used in floating wind systems. Given the increasing uncertainty over the future sustainability of the North Sea oil and gas industry, a number of suppliers are looking to diversify their portfolios by moving into offshore renewables. Floating wind is an obvious candidate which could safeguard local jobs in Scotland and create new export opportunities for Scottish businesses.

The ability for Scotland to leverage existing experience from the oil and gas sector, as well as benefit from the UK's position as the world's largest market for fixed-bottom offshore wind, may

[1] Please note that data for the study was submitted by concept designers and has not been independently validated.

accelerate the development of floating wind technology beyond what might be possible otherwise. While countries such as Japan, the United States, and France are keen to develop floating wind, the lack of either an established oil and gas sector or offshore wind industry may impede the rate of technology development and limit the cost reduction that can be achieved. By tapping into an existing knowledge base and benefitting from an established supply chain, Scotland can play a key role in supporting the global floating wind market.

Technology trends and cost drivers

There are currently over 30 floating wind concepts under development, each with their own respective strengths, which can vary by site depending on the water depth, seabed conditions, local infrastructure, and local supply chain capabilities. It is expected that over the coming years there will be greater consolidation in the market, with up to 10 concepts reaching full-scale demonstration and only a handful of devices progressing to commercial-scale deployments. The Carbon Trust conducted a quantitative assessment of 18 concepts currently on the market, based on information provided by the innovators, to understand the key technology trends, cost drivers, and barriers to commercialisation. For confidentiality reasons, the data, which was provided by platform designers, was grouped to compare concepts by typology (e.g. semi-submersible[2], spar-buoy, tension-leg platform, multi-turbine platforms, hybrid wind-wave devices[3]), rather than on an individual basis.

The analysis found that floating wind concepts have the potential for significant cost reduction from prototype to commercial phases of development, with capital expenditure (CAPEX) reaching £2.7m/MW, which would deliver a levelised cost of energy (LCOE) below £100/MWh (figure 0.1.1). Leading concepts are estimating even lower costs of £85-95/MWh (£2.4m/MW CAPEX), with further cost reduction expected over time that could improve the cost competitiveness of floating wind with other sources of electricity generation.

The data suggests that CAPEX and LCOE is, on average, similar between the three main typologies, although a comparison of individual concepts implies slightly lower LCOE in a handful of semi-submersible platforms, largely driven by simpler installation procedures. Some spar and TLP concepts are able to deliver lower foundation CAPEX[4], suggesting that optimisation in the installation process could deliver a lower cost solution. Concrete structures also performed very well, delivering lower CAPEX than steel alternatives.

However, it must be stressed that the data consists of estimates that have not been validated and, given the nascent state of the technology and with so few demonstrations in the water, a great deal of uncertainty exists when attempting to estimate the costs of commercial projects. The cluster of concepts in the £85-95/MWh range, which consists of concepts from each of the three main typologies, is a useful guide to the LCOE floating wind devices can achieve, but further work is needed to fully assess the cost competitiveness of the different concepts, which will also be influenced by site conditions, local infrastructure, and supply chain capabilities.

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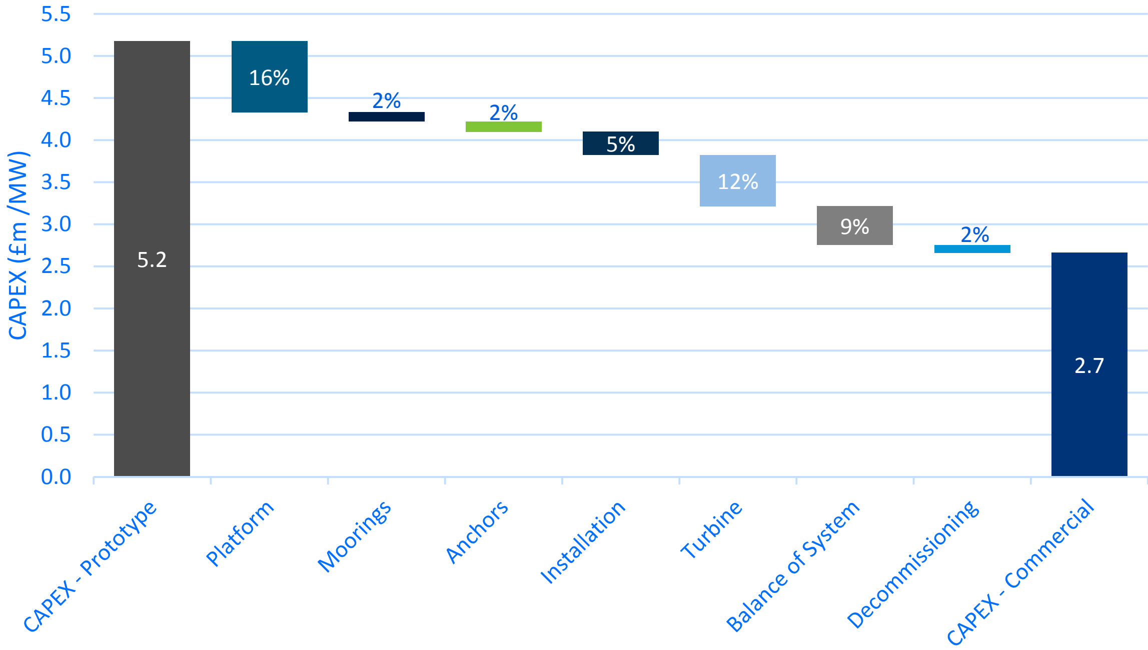
[2] Semi-submersible category includes caisson/barge concepts.

[3] Multi-turbine platforms and hybrid wind-wave devices were grouped together in the analysis.

[4] Foundation CAPEX includes the platform, moorings, and anchors only (i.e. excludes installation, turbine, balance of system, and, decommissioning).

Figure 0.1.1. Reduction in capital expenditure from prototype to commercial deployments



Key technical barriers

The Carbon Trust engaged with concept designers to identify and prioritise the most critical technical barriers which need to be overcome to commercialise floating wind technology. Challenges were ranked by cost reduction potential, degree of urgency, as well as the level of IP sensitivity (table 0.1.1). This was then used to identify the technical challenges that could be most appropriately addressed through industry collaboration.

Unsurprisingly, platform size was highlighted as the most critical challenge which could deliver the greatest cost savings. Installation procedures are also an area of importance, particularly for TLP and spar-buoy concepts. Further CAPEX savings are expected from developing floating transformer stations, advanced control systems, and improved mooring & anchoring systems. Meanwhile, OPEX savings could be achieved by developing robust procedures for port-side major repairs, for which the technical feasibility and cost benefit is currently poorly understood. It is also evident that while some challenges are more pressing in the short-term (e.g. advanced modelling tools), others will become increasingly important as the technology advances to commercial scale (e.g. floating transformer stations, high voltage dynamic cables, wake effects).

There is considerable variation between the priorities of different concepts, but also a number of common challenges where there is less IP sensitivity that could be addressed through industry collaboration. Thus while certain challenges, like platform size and turbine control systems, will need to be addressed by individual technology developers, others such as port-side O&M strategies, installation procedures, and wake effect modelling, could be overcome through collaborative R&D projects. There are also potential synergies with R&D activities in the wave and tidal sector on common challenges in moorings, anchors, dynamic cables, installation and O&M.

Table 0.1.1 Prioritisation of key technical barriers

Technical challenge	Cost reduction potential	Urgency	IP sensitivity
Platform size & weight	2.7	2.4	2.8
Installation procedures	2.5	2.2	1.8
Port-side O&M (major repair procedures)	2.3	2.2	1.0
Floating substations/transformer modules	2.3	2.0	2.0
Advanced control systems for floating WTGs	2.2	2.2	2.6
Mooring design & installation	2.2	2.1	2.4
Anchor design & installation	2.1	2.1	2.0
Advanced tank testing facilities	2.0	2.1	1.7
Wind farm operation (wake effects, yield, AEP)	1.9	2.1	1.0
Advanced modelling tools	1.9	2.5	2.0
High voltage dynamic cables	1.8	2.1	1.6
Bespoke standards for floating wind	1.8	2.0	1.0
Environmental impact	1.4	2.1	1.0

N.B. Scoring from 1-3; High = 3, Med = 2, Low = 1.

Recommendations

The lack of a clear market for floating wind has so far deterred private investors, developers, and OEMs from engaging with concept designers. There are signs that this is beginning to change, with more industry players showing an interest in floating wind technology. However, to attract the necessary private sector investment to take the technology forward and pull it to market, there is a need for higher levels of government funding to subsidise early demonstrations and pre-commercial arrays and to create targeted RD&D initiatives to overcome common challenges and build a stronger business case for floating wind.

The Carbon Trust has identified a suite of recommendations for the Scottish Government to address the barriers listed above and support the development of floating wind, defined at four levels:

- **Concept-specific RD&D initiatives** to support device development and provide funding for part and full-scale demonstrations
- **Test facility development** to establish the tank and offshore testing facilities needed to demonstrate promising concepts and test innovative component technologies
- **Component-level RD&D initiatives** to tackle common challenges
- **Evidence-base studies** to build a business case for investment in floating wind technology and identify the most effective policy interventions to attract private sector investment

Concept-specific RD&D would primarily involve funding prototypes and pre-commercial arrays, which are vital to prove the technical viability and cost reduction potential of floating wind devices. This could take the form of a successor subsidy mechanism to the enhanced ROCs in Scotland, possibly through a ring-fenced Contracts for Difference (CfD) pot for floating wind technology, or capital grants, as evident in Japan, France, Portugal, and the United States. In addition to funding support, government bodies in Scotland can help to create the test sites and facilities needed to host technology demonstrations and provide a platform for RD&D initiatives.

Component-level RD&D initiatives could build on technology demonstrations and foster greater collaboration between floating wind designers and developers, acting as a mechanism to pool both knowledge and resources. This could help to attract high levels of financial leverage to fund RD&D activities that might not otherwise be possible through individual concept designers. At a minimum, this would accelerate the level of RD&D activity and ensure that a coordinated approach is taken to avoid duplication and maximise impact. Collaborative RD&D could take the form of a single programme or several joint industry projects, focussing on technical challenges that are common to multiple concepts and do not infringe on IP sensitivities (see table 0.1), in areas such as installation procedures, port-side O&M, mooring and anchoring systems, and electrical systems.

Finally, there remains scope for further desk-based work to build a stronger business case for investment in floating wind technology. The Carbon Trust has identified several studies that could benefit the industry and better inform decision makers. These range from rigorous benchmarking of competing concepts in different site conditions, to detailed assessments of the cost reduction potential of floating wind and its competitiveness with fixed-bottom technology in the context of Scottish waters. A study to assess the wider socio-economic benefits of building a floating wind industry in Scotland would help to build a strong business case for government support.

Next steps for Scotland

The evidence suggests that floating wind has the potential to play a significant role in the UK, and particularly Scotland's, future energy mix. Even a modest UK deployment scenario of 40 GW of offshore wind in the UK by 2050 could consist of 8-16 GW from floating wind devices. From a Scottish perspective this could even be greater, since the point of cost convergence between fixed-bottom and floating wind is expected to be earlier in Scotland than other parts of the UK. However, the technology is still nascent and needs government support to reach commercial readiness and realise its cost reduction potential. In the near-term, funding is needed for full-scale demonstrations and pre-commercial arrays, together with targeted RD&D programmes to overcome technical challenges and unlock innovation.

Scotland has all the attributes to take a leading role in this field, leveraging its extensive experience and capabilities in offshore renewables and oil and gas. There appears to be a compelling case for Scotland to invest in floating wind technology, including investment in test facilities, subsidy support for pilot floating wind projects, and funding for RD&D initiatives to overcome technical challenges and drive cost reduction through innovation. All of these are expected to create economic and industrial benefits, both domestically and through exporting products and engineering services to emerging markets. Ultimately, floating wind presents an opportunity for Scotland to take the lead on an innovative, commercially-driven, and globally scalable technology to maintain its position as a world leader in offshore renewable energy.

1 Introduction

1.1 The Case for Floating Wind

1.1.1 Market Potential

The offshore wind market has so far been dominated by countries with relatively shallow water depths (<50m) and established maritime industries, often leveraging oil and gas experience. However, with the potential for fixed-bottom structures constrained over the long-term in many markets and mounting pressure to decarbonise and diversify energy portfolios, more countries are beginning to explore the potential for floating offshore wind. Particularly given that there are limited locations with shallow waters suitable for fixed-bottom foundations and that there is extensive wind resource in deep waters (50-200m), floating wind is potentially a highly scalable future energy source in a number of markets. In particular, there is significant potential and appetite for growth in Japan, the United States, and a number of European countries including the UK, Norway, France, Portugal, and Spain (table 1.1.1).

Table 1.1.1 Offshore wind resource and potential floating wind capacity in Europe, USA, and Japan (US NREL, 2012; EWEA, 2013; Marine International Consulting, 2013)

Country/Region	Share of offshore wind resource in deep water locations (>60m depth)	Potential floating wind capacity
Europe	80%	4,000 GW
USA	60%	2,450 GW
Japan	80%	500 GW

Europe

The potential for electricity generation from floating wind in Europe is vast. Over half of the North Sea is suitable for floating wind deployment, with water depths between 50m and 220m (Figure 1.1.1). On this basis, EWEA estimate that the energy produced from turbines in deep waters >50m in the North Sea alone could meet the EU's electricity consumption four times over (EWEA, 2013).

Figure 1.1.1.Sea depth around Europe (DNV-GL, 2014)

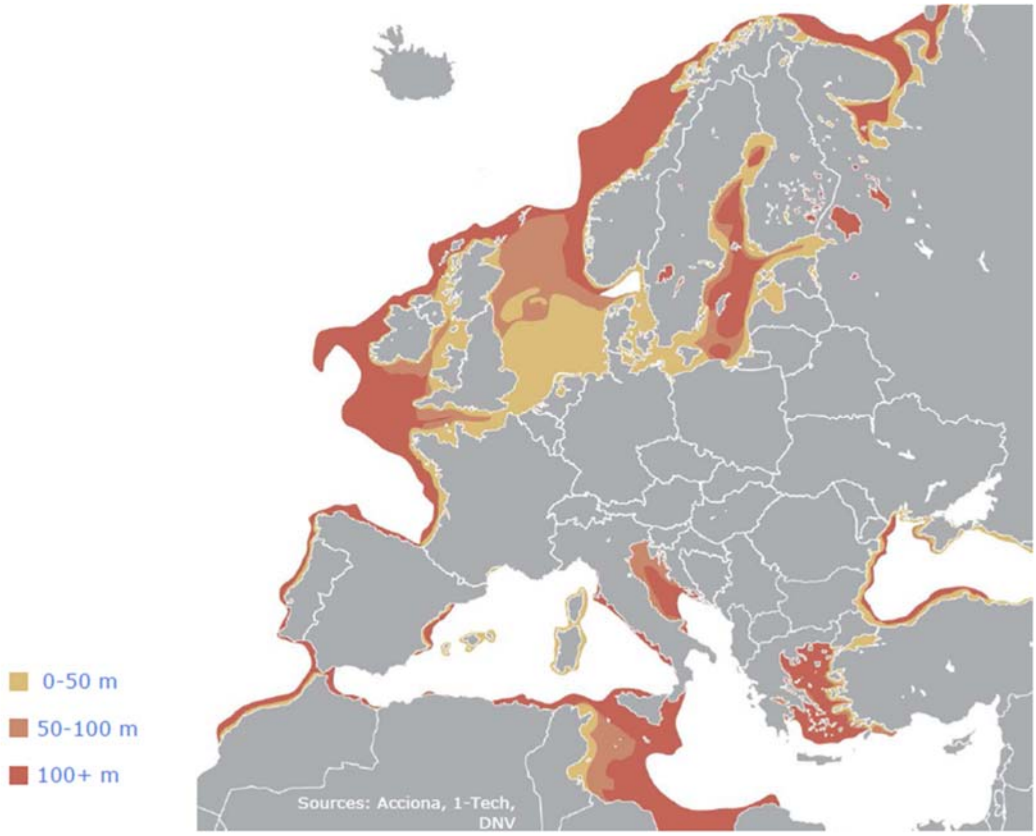
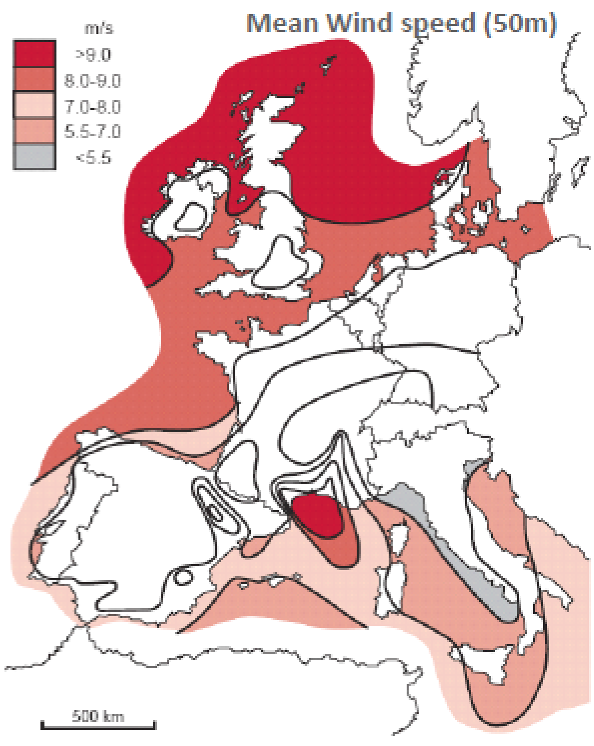


Figure 1.1.2. Mean wind speeds around Europe (EDP Renováveis, 2012)



There is also significant wind resource in the Atlantic, particularly off the coast of Scotland and England, and also in the west of France and off the coasts of Portugal and Spain, where deep water precludes fixed-bottom offshore wind development (Figure 1.1.2). Deep water is also prevalent in the Mediterranean, where the wind resource is generally less extensive than the North Sea and Atlantic coastline; although there are pockets of strong and moderate wind which could be well suited to floating turbines, particularly given that the less harsh marine conditions may allow for less conservative structural designs (ORECCA, 2011).

EU targets for offshore wind of 40 GW by 2020 and 150 GW by 2030 are expected to be achievable by predominantly using conventional fixed-bottom foundations in water depths under 50m. However, by 2050, offshore wind capacity in Europe could reach 460 GW, which can only be achieved by accessing deep water sites >50m using floating technology (EWEA, 2013). The 2030 target may also require a greater proportion from floating wind solutions if they prove to be cost competitive and the development of floating wind technology is accelerated. While offshore wind deployment up to 2030 is expected to be dominated by the significant growth of fixed-bottom wind farms, from 2030 it is likely that adequate sites will become scarcer and more costly to develop with fixed-bottom structures, further from shore and in sites with challenging seabed and/or met-ocean conditions. Floating wind technology could thus be used to exploit deep water locations closer to shore, and the added flexibility of floating structures means that it has the potential to be highly scalable.

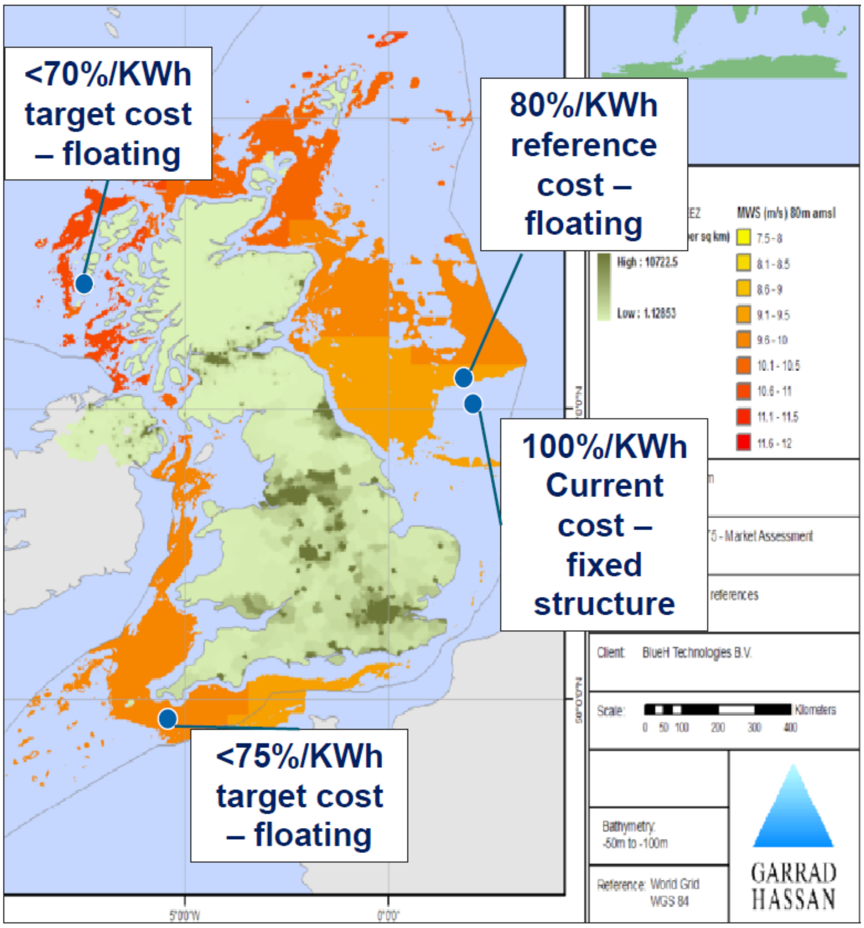
UK

The UK is blessed with excellent offshore wind resource and access to the shallow continental shelf of the North Sea. However, there is also significant resource in deep water >50m, where wind speeds are often stronger and more consistent than in shallower locations. The highest mean wind speeds in the UK are in Scottish waters and off the south-west coast of the UK, where deep water locations are abundant. Given the importance of energy yield for wind farm economics, the Energy Technologies Institute (ETI) estimate that deploying floating wind in these locations to access this stronger wind resource could result in a lower levelised cost of energy (LCOE) compared with some fixed-bottom UK Round 3 sites (ETI, 2009). Indeed, there is already evidence to suggest that more consistent wind resource in deep water locations can lead to higher load factors in floating turbines[5].

The distribution of sites suitable for floating wind in the UK is expected to differ to fixed-bottom wind. While the best sites for fixed-bottom offshore wind are found off the east coast of England in shallow waters (<50m depth), the opportunities for floating wind are concentrated off the coast of Scotland and Wales, where near-shore deep water sites (>50m depth) are located, and the geology and met-ocean conditions are suitable for floating devices (figure 1.1.3). In Scotland, there are extensive deep water locations to the east, north, and west of the country, with 123 GW of the 169 GW offshore wind potential located in water depths exceeding 60m (Scottish Enterprise, 2015). Licensed sites for fixed-bottom offshore wind in Scotland are largely in water depths over 40-45m and in complex seabed conditions, which suggests that the low-hanging fruit available for offshore wind may be smaller than elsewhere in the UK. On this basis, commercialised floating wind projects would have the potential to unlock lower cost sites in Scottish waters.

[5] Hywind 2.3 MW demonstration in Norway has achieved average load factors of up to 50%, compared with 35-40% in typical fixed-bottom offshore turbines and 25-30% in typical onshore turbines.

Figure 1.1.3. Average wind speeds in UK waters 50-100m deep, with ETI indicative cost analysis (ETI, 2009)



Note: This figure is based on ETI projects carried out from 2007 to 2009. Further work has been carried out by the ETI since 2009, most recently in their floating platform project http://www.eti.co.uk/project/floating-platform-system-demonstrator/. This further work has refined the ETI's insights and they will be reported in an ETI insights paper later in 2015. This later work has highlighted the strategic importance of floating wind in Scottish and Welsh waters.

The 100%/kWh represents an estimate of the LCOE for a fixed bottom offshore wind project at a UK Round 3 location, near the Dogger Bank. The 2009 work suggested that floating projects could achieve LCOE as low as 70%/kWh relative to the Round 3 baseline. This is due to accessing higher and more consistent winds, along with making use of sites close enough to shore to be economically attractive. The ETI's more recent work has confirmed this, suggesting that LCOE of less than £85/MWh is achievable, with the potential for further improvement.

More recent ETI work also indicates that the waters around the south-west of England may not be as suitable (as opposed to the figure above), due to a combination of 50 year wave height, geology, and water depth that are less suitable for floating wind devices.

1.1.2 Cost Competitiveness

Critical to exploiting the potential wind resource in deep water locations is the cost competitiveness of floating wind versus more mature fixed-bottom offshore wind technology, as well as other energy sources. The absence of commercial floating wind farms makes it difficult to compare cost competitiveness, since existing prototypes have understandably high costs and are not a useful reference point for comparative analysis with operational fixed-bottom wind farms. However, studies by EWEA (2013) and DNV-GL (legacy GL Garrad Hassan, 2012) using cost estimates from industry suggest that floating designs could be competitive in terms of the levelised cost of energy (LCOE) with fixed-bottom foundations in water depths greater than 50m. Beyond 50m the cost competitiveness of floating wind improves exponentially. However, despite floating wind being more competitive than fixed-bottom foundations in >50m, the technology is not yet commercially competitive when compared to other energy sources.

Critically, this cost competitiveness has yet to be demonstrated, hence it can be said that floating wind is still in its infancy. Further research, development, and demonstration (RD&D) activity is therefore vital if cost parity with fixed-bottom wind farms is to be realised. Floating devices will need to de-risked and demonstrated at increasing scale to prove their feasibility and cost reduction potential. Once proven, and with sufficient government support, floating wind can attract investment for commercial deployment and benefit from the learning factors and economies of scale that this will bring.

A more detailed cost analysis for floating wind is included in section 2.7.

1.1.3 Market Outlook

The point in time at which floating wind will become competitive with conventional fixed-bottom offshore wind is uncertain and will be partly dependent on the rate at which shallow fixed-bottom sites are developed, as well as the level of public and private sector support to invest in RD&D and build sufficient volume to unlock the additional savings from learning and scale factors. In the context of the available sites for offshore wind development around the UK, the ETI (2015) expect that if offshore wind deployment is constrained to just 20 GW by 2050, floating wind is unlikely to play a significant role in the UK's energy mix. However, if deployment reaches 40 GW, floating wind could contribute 8-16 GW of this capacity, and even more if the upper scenario of 55 GW offshore wind is attained. The point of cost convergence between fixed-bottom and floating wind is expected to be even lower in Scotland given the more challenging sites for fixed-bottom wind farms, which could create additional opportunities for floating wind developers.

Nevertheless, based on current market trends, it is expected that fixed-bottom offshore wind farms will continue to dominate up to 2030, but the next 5-10 years will be an important development period for floating technology, with more prototype demonstrations and pilot arrays to prepare the technology for commercial projects from 2020-2025. This could be closer to 2020 if an ambitious deployment target is outlined for offshore wind and the development of floating solutions is accelerated, but more distant if there is insufficient government support to demonstrate the technologies and stimulate the market. By taking a lead in RD&D in this area, Scotland, and other parts of the UK, would be well-positioned to capture significant export opportunities when deployment achieves scale, particularly given the potential size of markets in the US, Japan, and elsewhere in Europe.

1.2 Aim and Scope of this Study

The Carbon Trust undertook a comprehensive review of the existing literature on floating wind to identify key knowledge gaps and identify areas which require further research (see Appendix section 7.1). Considering the findings of the literature review and gap analysis, this study will present an up-to-date snapshot of the status of floating wind technology, consolidating information and knowledge accumulated to date, including:

- The range of floating concepts currently under development
- Component technologies used in floating wind systems (e.g. moorings, anchors)
- Cost analysis of floating versus fixed-bottom offshore wind structures and assessment of the commercial feasibility of floating wind as a cost-effective energy source
- Government support for floating wind, including RD&D initiatives
- Test facilities and offshore sites for floating wind research and demonstration

The study will also conduct new research and analysis to:

- Provide a quantitative and qualitative comparison between the main typologies, including:
    - Technology design specifications
    - Fabrication & supply chain
    - Installation
    - Operations & Maintenance (O&M)
    - Cost – CAPEX, OPEX, and LCOE
- Identify key infrastructure and supply chain requirements for floating wind, and assess Scottish capabilities to meet these requirements
- Plot the technology readiness of different floating concepts under development
- Highlight the key technical and market barriers to commercialising floating wind technology
- Identify RD&D opportunities to overcome the challenges identified
- Produce a set of recommendations for the Scottish Government and industry to accelerate the development of floating wind and maximise benefits for Scotland

2 State of the Industry

Market:

- There is extensive wind resource in deep water locations (>50m depth) suitable for floating wind foundations, particularly in Europe, Japan, and the United States.
- In the UK, while fixed-bottom offshore wind is expected to dominate in shallow seabed conditions off the east of England, there is significant potential for floating wind to access near-shore deep water sites in Scotland and off the south-west coast of the UK.

Technology:

- There are three dominant typologies (semi-submersible, spar-buoy, and tension-leg platform - designs adapted from the oil and gas industry), each with different strengths and weaknesses, influenced by site conditions.
- Over 30 concepts are currently under development, with two-thirds emanating from Europe, though the emerging offshore wind markets in Japan and the USA are also very active.
- Design standards are being developed by DNV-GL and ABS, adapting existing standards in the offshore renewables and oil & gas industries, but there is considerable further work to be done to develop appropriate fit-for-purpose standards for the floating wind industry.

Cost competitiveness:

- Floating wind has the potential to reach cost parity with fixed-bottom offshore wind, with the higher CAPEX of the platform, moorings, and anchors negated by lower installation costs and lower OPEX driven by cheaper repair costs for major components.
- Demonstrating and validating the cost reduction potential is a critical next step for the industry.

Research, development, and demonstration initiatives:

- Early prototypes of floating wind concepts are expensive and require significant government support.
- Support so far has been concept-specific, with grants provided for scaled testing and a handful of full-scale demonstrations.
- There is scope for component-specific RD&D initiatives to tackle common challenges, in addition to further full-scale demonstrations and first arrays.
- Several demonstrations are in the pipeline to 2018 with cumulative capacity of ~240 MW.
- DNV-GL 'Win-Win' joint industry project could open further opportunities for commercial demonstrations of floating wind concepts.

Test facilities:

- Tank testing facilities used to date in Europe are suitable, but not advanced. The FloWave ocean energy facility at Edinburgh University could support model testing in complex wave and current environments similar to the North Sea.
- Tank testing campaigns at advanced facilities could support further concept de-risking and optimisation to close the gap between scaled testing to full-scale demonstration.
- There is an abundance of deep water locations appropriate for floating wind turbines, but the challenge is identifying sites near to the requisite infrastructure (grid connection, port facilities), and then obtaining consent for these sites.

2.1 Floating Wind Foundation Typologies

There are three dominant classifications of floating wind structures:

- Semi-submersible platform: Buoyancy stabilised platform which floats semi-submerged on the surface of the ocean whilst anchored to the seabed with catenary mooring lines. Often requires a large and heavy structure to maintain stability, but a low draft allows for more flexible application and simpler installation. *Examples: WindFloat (by Principle Power); Damping Pool (by IDEOL); SeaReed (by DCNS).*

- Spar-buoy: A cylindrical ballast-stabilised structure which gains its stability from having the centre of gravity lower in the water than the centre of buoyancy. Thus, while the lower parts of the structure are heavy, the upper parts are usually lighter, thereby raising the centre of buoyancy. The simple structure of the spar-buoy is typically fairy easy to fabricate and provides good stability, but the large draft requirement can create logistical challenges during assembly, transportation, and installation, and can constrain deployment to waters >100m depth. *Examples: Hywind (by Statoil); Sway (by Sway); Advanced Spar (by Japan Marine United).*

- Tension leg platform (TLP): A semi-submerged buoyant structure, anchored to the seabed with tensioned mooring lines, which provide stability. The shallow draft and tension stability allows for a smaller and lighter structure, but this design increases stresses on the tendon and anchor system. There are also challenges with the installation process and increased operational risks if a tendon fails. *Examples: PelaStar (by Glosten); Blue H TLP (by Blue H Group); Eco TLP (by DBD Systems); GICON-SOF (by GICON).*

Figure 2.1.1. Floating wind foundation typologies (DNV-GL, 2014)

Variations of these typologies also exist, including:

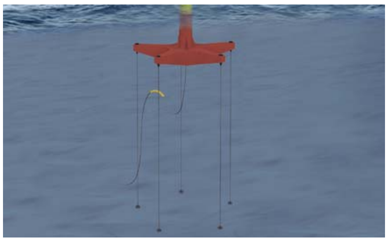
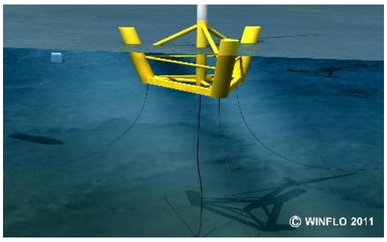
- **Multi-turbine floating platforms:** Large semi-submersible floating platforms that can support more than one turbine. *Examples: Hexicon (by Hexicon); WindSea (by FORCE Technology)*
- **Hybrid wind/wave floating devices:** A wind turbine erected on a platform which includes a submerged wave energy device. *Examples: SKWID (by MODEC); Poseidon P80 (by Floating Power Plant)*

There is no clear winner with regards to typology, with each typology and concept carrying their own strengths and weaknesses, often dictated by specific site conditions. Nevertheless, there are some broad over-arching trends that are evident in each, summarised below.

Typology	Strengths	Weaknesses
Semi-submersible	✓ Flexible application due to the ability to operate in shallow water depths ✓ Low vessel requirement – only basic tug boats required ✓ Onshore turbine assembly ✓ Amenable to port-side major repairs	× High structural mass to provide sufficient buoyancy and stability × Complex steel structures with many welded joints can be difficult to fabricate × Potentially costly active ballast systems
Spar-buoy	✓ Simple design is amenable to serial fabrication processes ✓ Few moving parts (no active ballast required) ✓ Excellent stability	× Constrained to deep water locations × Offshore turbine assembly requires dynamic positioning vessels and heavy-lift cranes × Large draft limits ability to tow the structure back to port for major repairs
Tension leg platform	✓ Low structural mass ✓ Onshore turbine assembly ✓ Few moving parts (no active ballast required) ✓ Excellent stability	× High loads on the mooring and anchoring system × Challenging installation process × Bespoke installation barge often required
Multi-turbine platform	✓ Net reduction in structural mass per turbine ✓ Platform can be used to site auxiliary equipment and facilities	× Wake effects can reduce yield × Large platform could be susceptible to higher bending loads × Large platform can cause fabrication and installation challenges
Hybrid wind/wave	✓ Merging wind and wave technologies can reduce intermittency of supply and increase total power output	× Challenge to integrate two energy generation systems × Increased floater motion can increase turbine loads × High structural mass × Complex O&M

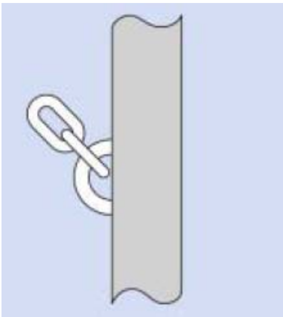
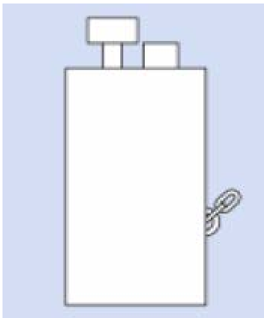
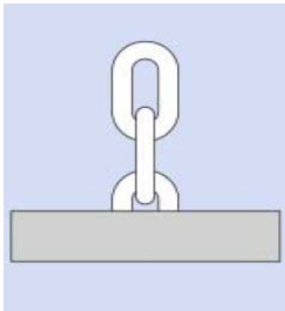
2.2 Mooring and Anchoring Systems

The most common mooring configurations are either taut-leg mooring systems, which are used with TLP concepts, or catenary mooring systems, which are used with spar-buoy and semi-submersible concepts. Some concepts will also adopt a semi-taut mooring system, which is a mix between both characteristics, though this is less common. An overview of these configurations is included below.

Taut-leg	Catenary	Semi-taut
		
Example: Glosten PelaStar	*Example: DCNS SeaReed*	*Example: Aerodyn Nezzy*
• Synthetic fibres or wire which use the buoyancy of the floater and firm anchor to the seabed to maintain high tension for floater stability	• Long steel chains and/or wires whose weight and curved shape holds the floating platform in place. Lower section of mooring chain rests on the seafloor, supporting the anchor and acting as a counterweight in stormy conditions	• Synthetic fibres or wires usually incorporated with a turret system, where a single point on the floater is connected to a turret with several semi-taut mooring lines connecting to the seabed
• Small footprint	• Large footprint	• Medium footprint
• Vertical loading at anchoring point	• Horizontal loading at anchoring point	• Loading typically at ~45 degrees to anchoring point
• Large loads placed on the anchors – requires anchors which can withstand large vertical forces	• Long mooring lines, partly resting on the seabed, reduce loads on the anchors	• Medium loads on the anchors
• Very limited horizontal movement	• Some degree of horizontal movement	• Limited horizontal movement, but full structure can swivel around the turret connection
• High tension limits floater motion (pitch/roll/heave) to maintain excellent stability	• Weight of mooring lines limits floater motion, but greater freedom of movement than taut-leg	• Single connection point makes the platform susceptible to wave induced motion
• Challenging installation procedure	• Relatively simple installation procedure	• Relatively simple installation procedure
• Minimal disruption to the seabed (small footprint)	• Lower section of chain rests on the seabed, resulting in more disruption (large footprint)	• Low level of disruption (medium footprint)

There are a number of anchoring solutions available, depending on the mooring configuration, seabed conditions, and holding capacity required. Catenary mooring configurations will often use drag-embedded anchors to handle the horizontal loading, though piled and gravity anchors are still applicable, while taut-leg moorings will typically use either drive piles, suction piles, or gravity anchors to cope with the large vertical loads placed on the mooring and anchoring system. The size of the anchor is also variable, with larger and heavier anchors able to generate a greater holding capacity.

Ultimately, anchor choice will be project and site specific, often dictated by the seabed conditions. Higher holding capacities are usually generated in sands and hard clays than in soft clays, although where penetration is difficult in firm soils, gravity base or piled solutions might be required. A summary of the main anchor types is detailed below, but there is great variety even within these typologies. All are proven concepts which have been used extensively in the marine and oil & gas industries.

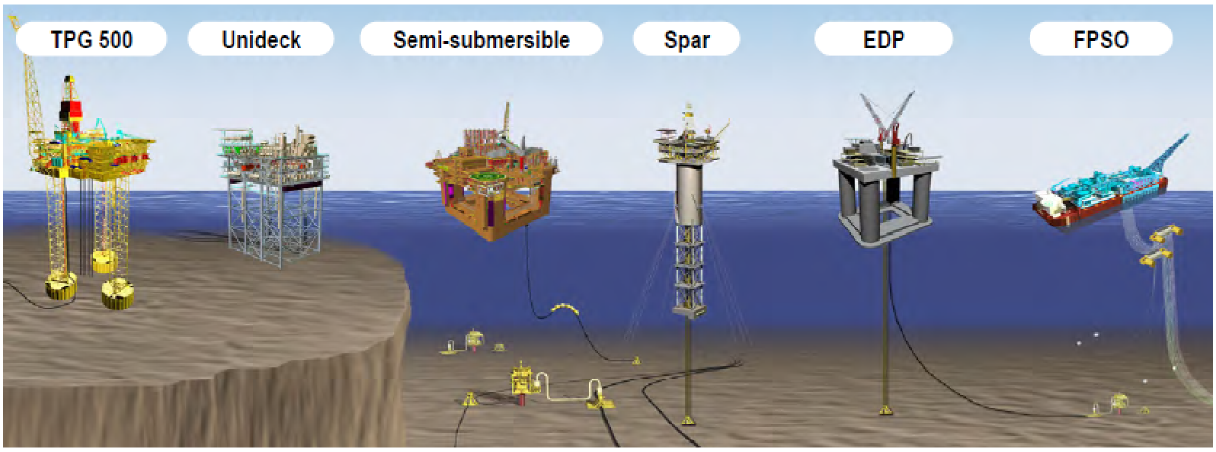
Drag-embedded	Driven pile	Suction pile	Gravity anchor
			
• Best suited to cohesive sediments, though not too stiff to impede penetration	• Applicable in a wide range of seabed conditions	• Application constrained by appropriate seabed conditions - not suitable in loose sandy soils or stiff soils where penetration is difficult	• Requires medium to hard soil conditions
• Horizontal loading	• Vertical or horizontal loading	• Vertical or horizontal loading	• Usually vertical loading, but horizontal also applicable
• Simple installation process	• Noise impact during installation (requires hammer piling)	• Relatively simple installation, less invasive than other methods	• Large size and weight can increase installation costs
• Recoverable during decommissioning	• Difficult to remove upon decommissioning	• Easy removal during decommissioning	• Difficult to remove upon decommissioning

2.3 Synergies with Other Industries

The three dominant floating foundation typologies for floating wind turbines, and the associated component technologies (e.g. mooring, anchors), are based on designs traditional used in other industries, particularly oil and gas. Having initially exploited oil wells in shallow waters using fixed-bottom structures, the identification of significant oil reserves further offshore in deep waters created the need for floating structures. This need was met with the development of spar, semi-submersible, and TLP structures which could access deep water locations and extract significant volumes of oil (figure 2.3.1). However, while the typologies are similar, the structures themselves are very different and must meet different needs. For example whereas oil and gas industry requires bigger but fewer structures, offshore wind will require installation of a large number of smaller structures, which impacts greatly on the design, fabrication, installation, and operational characteristics of the structures.

Offshore wind could mirror the trend seen in the oil and gas industry when it moved from fixed to floating foundations during the 1970s, in order to access oil wells in deeper waters further from shore. As with wind, one of the main obstacles oil and gas had to overcome was the perceived risk of moving to a new technology.

Figure 2.3.1. Floating structures used in the oil and gas industry (Maine University, 2010)



2.4 Review of Existing Floating Wind Concepts

There are a number of floating wind concepts currently under development, but there is no clear winner with regard to which is most likely to be deployed at scale in the future. In all likelihood there will not be a single winning concept, but a range of leading devices suitable for different site conditions, and influenced by local infrastructure and supply chain capabilities. This section contains an overview of the various concepts currently under development which are vying for market leader position in the race to commercialise their designs.

Note: TRL levels are expressed on a scale from 0-7 (see table 4.1.1 in section 4.1 for TRL descriptions).

2.4.1 Semi-Submersible Platforms

WindFloat	Principle Power			
	Classification:	Semi-sub	Primary material:	Steel
	Depth range:	40m-1000m	Moorings:	3 catenary
	Turbine axis:	Horizontal	No. blades:	3
	Industrial partner(s):	EDPR; Repsol; Pilot Offshore; Atkins	TRL:	4
	Full-scale prototype:	2011	Pre-commercial array:	2018

WindFloat is one of the more mature concepts in the market, having had a 2 MW unit installed off the coast of Portugal since 2011. The design consists of a semi-submersible hull with three columns, one of which supports the turbine.

A static water ballast is used to achieve the desired operating draft while entrapment (heave) plates at the base of each column provide dynamic stability to dampen wave and turbine induced motion. This stability performance allows for the use of existing commercial wind turbine technology. The design is therefore considered to be 'turbine agnostic', with the ability to support most conventional three-blade upwind turbines with only minor design modifications.

The mooring system employs conventional components such as chain and polyester lines to minimise cost and complexity. Through the use of pre-laid drag embedded anchors, site preparation and impact is minimized.

The design is benefitting from its first-mover position in the market and there are ambitious plans to scale up development over the next 5-10 years, with projects planned in the US (Oregon, 30 MW; Hawaii, 2 x 408 MW), Scotland (Kincardine, 48-50 MW), and Portugal (Aguçadoura, 25 MW).

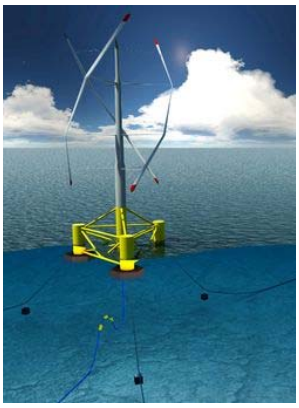
Damping Pool IDEOL

Classification:	Caisson/barge	Primary material:	Concrete or steel
Depth range:	35m+	Moorings:	6-9 catenary
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	Hitachi Zosen; Adwen	TRL:	3
Full-scale prototype:	2015	Pre-commercial array:	Undisclosed

The IDEOL platform is a square concrete hull with a central opening to create a patented 'damping pool' system that uses the entrapped water to minimise floater motions, resulting in strong hydrodynamic performance. The low floater motion means that the concept is compatible with conventional offshore turbines in the market, with only minor tower upgrades and adapted blade pitch control software required align with the floater's behaviour. The design can also be constructed using steel, but delivers greater cost reduction and higher local content when using concrete. The concept is classified as a caisson/barge concept, but for the purposes of this study it has been grouped as a semi-submersible design to avoid breach of confidential data in our analysis.

The modular structural design and use of concrete as the primary material means that the design is less prone to price volatility and is highly amenable to mass production with on-site construction, high local content, and versatile construction methods, depending on local infrastructure and capabilities. IDEOL has also developed its own patented 'mobility' solution which allows the floater to move along its mooring lines, allowing it to alter its position to reduce wake losses in an array.

IDEOL have an initial 2 MW demonstration slated for installation at the SEM-REV test site in 2015, part funded by the European Commission's FLOATGEN and French Government (ADEME) OCEAGEN initiatives. IDEOL have also secured a partnership with Hitachi Zosen to deploy the IDEOL concept in Japan.

VERTIWIND	Technip/Nenuphar			
	Classification:	Semi-sub	Primary material:	Steel
	Depth range:	50m+	Moorings:	3 catenary
	Turbine axis:	Vertical	No. blades:	3
	Industrial partner(s):	EDF Energy; Areva	TRL:	3
	Full-scale prototype:	2016	Pre-commercial array:	2018

Technip and Nénuphar have developed a floating wind structure to accommodate vertical axis wind turbines, which the designers claim can reduce the aerodynamic loads on the structure, with the low centre of gravity improving stability and minimising the gyroscopic effects, which allow for a smaller and cheaper platform. Nénuphar claims a 30% reduction in investment and operations and maintenance costs compared to current offshore turbines. The design is benefitting from two strong industrial partners, with EDF Energy and Areva supporting the development of the design.

An onshore prototype of the vertical axis wind turbine is currently in operation at Fos-sur-Mer, and a 2 MW unit is expected to be deployed in the Mediterranean in 2016, with support from the European Commission through the 'INFLOW' project. Following this initial pilot, there are plans for a 13 turbine 34 MW wind farm in 2018.

SeaReed	DCNS			
	Classification:	Semi-sub	Primary material:	Steel
	Depth range:	50-200m	Moorings:	Undisclosed
	Turbine axis:	Horizontal	No. blades:	3
	Industrial partner(s):	Alstom	TRL:	3
	Full-scale prototype:	2018	Pre-commercial array:	2020

Marine contractor DCNS and turbine manufacturer Alstom have joined forces to develop an integrated solution for floating wind. The concept, initially developed under the WinFlo initiative and now supported under the SeaReed project, is a semi-submersible composed of a central cylindrical column, which supports the turbine, plus 3 external cylindrical columns linked to the central column by pontoons. The modular design allows for serial production at a rate of up to 50 turbines per year.

Having initially been designed to support a two-blade turbine, the partnership with Alstom will see the floater designed to support the 6 MW Haliade machine. The partnership between DCNS and Alstom will create an integrated solution which optimises the stability and performance of the complete system to reduce loads and maximise the power output of the turbine.

A pilot demonstration is expected to be installed at Le Croisic, Brittany, in 2018 before scaling up to pre-commercial and commercial scale from 2020.

Tri-Floater — GustoMSC

Classification:	Semi-sub	Primary material:	Steel
Depth range:	50-300m	Moorings:	3 catenary
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	TBC	Pre-commercial array:	TBC

The GustoMSC Tri-Floater is a 3 column braceless semi-submersible unit designed for high reliability and easy manufacturing, installation, maintenance and inspection. GustoMSC has used its extensive experience of offshore structural design to develop a slender floater without braces, which allows for easier fabrication, and natural periods that are outside the range of wave periods, resulting in very mild motions and accelerations. This stability means that no active ballast system is required to limit roll and pitch, which the designers claim makes the concept more robust and cost-effective.

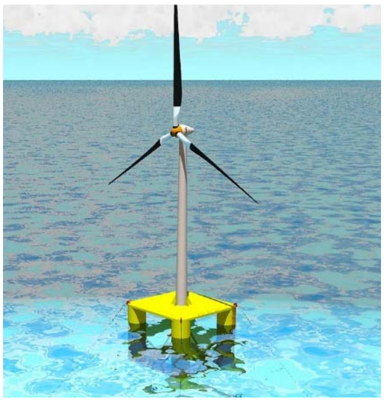
The concept has undergone advanced simulations and model testing to verify its performance and further optimise the design.

SPINFLOAT — EOLFI/GustoMSC

Classification:	Semi-sub	Primary material:	Steel
Depth range:	50-300m	Moorings:	3 catenary
Turbine axis:	Vertical	No. blades:	3
Industrial partner(s):	-	TRL:	Undisclosed
Full-scale prototype:	TBC	Pre-commercial array:	TBC

SPINFLOAT is a variation on the GustoMSC Tri-Floater, adopting a vertical axis turbine on the floater platform instead of a conventional horizontal axis turbine. The vertical axis design is being developed by EOLFI, working closely with GustoMSC to optimise an integrated solution.

Nautilus Semi-Sub — Nautilus Floating Solutions



Classification:	Semi-sub	Primary material:	Steel
Depth range:	60-150m	Moorings:	4
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	TBC	Pre-commercial array:	TBC

Nautilus Floating Solutions is a consortium of five leading companies in advanced technology aiming to develop a semi-submersible floating wind platforms for international markets. The NAUTILUS technology consists of a four column ring pontoon semi-submersible unit with heave plates and a catenary mooring system. The wind turbine is located centrally relative to the columns which provide buoyancy to support the turbine and allow sufficient water plane inertia to maintain stability. The horizontal plates at the bottom and in between the columns increase the added mass, thus shifting the natural period away from the wave motions and increasing the viscous damping in roll, pitch, and heave. The water ballast, which is located inside the bottom of the columns, acts as a static ballast to lower the platform to its target operational draft. An active ballast system is then used to compensate changes in wind speed and directions, taking water into and off each column to compensate for the wind loading on the turbine.

Nezzy SCD — Aerodyn Engineering

Classification:	Semi-sub	Primary material:	Concrete
Depth range:	35-200m	Moorings:	5 semi-taut (turret system)
Turbine axis:	Horizontal	No. blades:	2
Industrial partner(s):	-	TRL:	2
Full-scale prototype:	TBC	Pre-commercial array:	TBC

The Nezzy floater has been designed by Aerodyn to support its 2-blade super compact drive (SCD) turbine technology. The floater consists of a concrete y-shaped floating unit with a cylindrical plastic-composite buoy at the end of each leg to provide added buoyancy. Concrete brings benefits of a cheaper and less volatile material cost and the slender foundation design further reduces overall CAPEX. A semi-taut turret mooring system at the end of the longest leg which can rotate to align the turbine with the wind flow. The integrated design also incorporates a number of turbine innovations. The droplet-shaped tower reduces wind resistance and, for better load distribution, the turbine head loads are distributed into the foundation with guyed ropes, which eliminate tower bending moments and result in significant mass and cost savings. The tower is angled at 10 degrees downwind and the drivetrain is mechanically adapted to acceleration forces caused by floating wind movements. Despite being in the early stages of development, the concept's cost reduction potential was recognised in being named the Gold Medal Winner in the Wind Power Monthly Turbine Innovations of the Year 2014.

TetraFloat — TetraFloat Ltd.

Classification:	Semi-sub	Primary material:	Steel
Depth range:	30-200m	Moorings:	1 catenary chain
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	TBC	Pre-commercial array:	TBC

TetraFloat is a floating platform comprising structural members on the edges of a tetrahedron. The innovative lightweight design reduces material costs and adopts a downwind alignment to reduce stresses in the tower, enabled by a single mooring line which causes the full structure to free-yaw into the prevailing wind. The concept has been basin tested with scaled prototypes.

VolturnUS — DeepCWind Consortium

Classification:	Semi-sub	Primary material:	Concrete
Depth range:	Undisclosed	Moorings:	Undisclosed
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	2018	Pre-commercial array:	TBC

The VolturnUS is a semi-submersible platform developed at the University of Maine's Advanced Structures and Composites Centre through the DeepCWind Consortium. The design uses advanced materials that help to reduce the overall cost of the system while ensuring high performance and efficiency; namely, a lower cost concrete foundation in addition to a lighter weight composite tower.

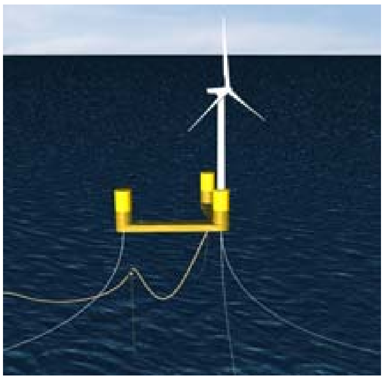
A 1:8 scale 0.02 MW prototype was installed in the Gulf of Maine in 2013 and there are plans for a full-scale demonstration with two 6 MW turbines deployed off the coast of Maine. The project narrowly missed out on a $47m DOE grant for the demonstration project, but remains an alternative should either of the three winning projects fail to be developed, with $40m private sector investment already secured. This forms part of a long term goal to install up to 5 GW of floating wind in Maine by 2030.

Compact Semi-Sub — Mitsui Engineering & Shipbuilding

Classification:	Semi-sub	Primary material:	Steel
Depth range:	Undisclosed	Moorings:	6 catenary
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	Marubeni Corporation	TRL:	4
Full-scale prototype:	2013	Pre-commercial array:	TBC

Four column semi-submersible platform using a standard catenary mooring configuration. The structure was installed off the coast of Fukushima, Japan, in 2013 supporting a 2 MW Hitachi turbine. The device has already survived two typhoon events and achieved availability rates of ~88%. As the first floating wind structure at the Fukushima FORWARD project, the design was highly conservative, with a large mass and high steel content leading to high capital expenditure. However, subsequent installations will aim to reduce the platform dimensions and optimise the design to reduce the overall system cost.

V-Shape Semi-Sub — Mitsubishi Heavy Industries



Classification:	Semi-sub	Primary material:	Steel
Depth range:	Undisclosed	Moorings:	8 catenary
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	Marubeni Corporation	TRL:	3
Full-scale prototype:	2015	Pre-commercial array:	TBC

V-shape semi-submersible platform with the turbine located on one of three columns which provide additional buoyancy for the structure. A first full-scale demonstration is slated for installation in 2015 supporting the 7 MW MHI SeaAngel turbine, which will make it the world's largest floating wind device. As with the compact semi-sub, the more conservative platform design for the first demonstration will require further optimisation to reduce costs for commercial deployment.

2.4.2 Spar-Buoys

Hywind	Statoil			
	Classification:	Spar	Primary material:	Steel or concrete
	Depth range:	100-500m	Moorings:	3 catenary
	Turbine axis:	Horizontal	No. blades:	3
	Industrial partner(s):	Statoil	TRL:	4
	Full-scale prototype:	2009	Pre-commercial array:	2017

The Hywind spar-buoy is arguably one of the most mature floating concepts under development, having had a 2.3 MW prototype deployed off the coast of Norway since 2009. Hywind consists of a traditional spar buoy structure, with draft of 70-90m, and a catenary 3-line mooring system. There are plans to scale-up the device and install 5 x 6 MW turbines in a pre-commercial array off the coast of Scotland in 2017.

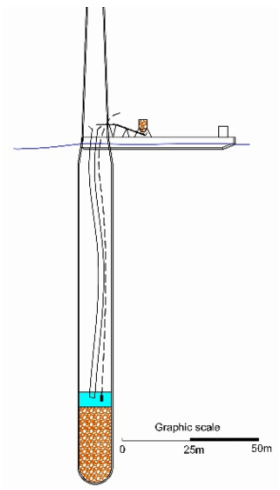
The design has been modified from the original prototype to allow for a shorter but thicker hull, which should result in a net reduction to material costs, as well as open up a wider market for its application. The ballast will also be adapted from a water ballast in the first Hywind to a stone ballast in the new design, in order to cope with the additional loads of the larger 6 MW turbines. In combination, Statoil expect these adaptations and optimisations to reduce LCOE by two-thirds from the 2.3 MW demonstration, with further cost reduction potential for commercial deployment. However, the exact dimensions and mass of the spar will be site-dependent.

Sway — Sway A/S

Classification:	Spar	Primary material:	Steel
Depth range:	55-300m	Moorings:	1 steel pipe
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	TBC	Pre-commercial array:	TBC

Sway consists of a continuous tower/foundation which is anchored to the seabed using a tension-torsion leg which is equipped with a passive subsea yaw swivel (i.e. the entire tower yaws together with the turbine when the wind changes direction). A downwind-oriented turbine allows for more tower tilt and a passive yaw swivel at the bottom of the tower allows for stiffening in the tower with wire stays upwind of the tower to reduce bending moments. The net effect is claimed to be up to ~50% less combined steel weight of the tower/foundation compared to conventional spar concepts. The Sway single anchor leg system can reportedly save 60-70% of the anchor system costs compared to a slacked moored system, with 8-10 times less anchor forces than a conventional multi-leg TLP design. A 0.15 MW prototype was installed off the coast of Norway in 2011, and Sway is now seeking support for a full-scale demonstration.

WindCrete — Universitat Politècnica de Catalunya



Classification:	Spar	Primary material:	Concrete
Depth range:	150-1000m	Moorings:	3 catenary
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	TBC	Pre-commercial array:	TBC

The WindCrete solution is a conventional spar-buoy floater designed for application in deep waters >150m. The spar consists of a monolithic concrete design, including both the tower and the floater, to reduce steel content. To avoid cracking and fatigue in the marine environment, the structure is completely post-tensioned with steel tendons in a longitudinal direction. The ballast makes use of black slag, a by-product of electrical furnaces, to reduce costs and its environmental footprint.

Hybrid concrete-steel spar — Toda Construction

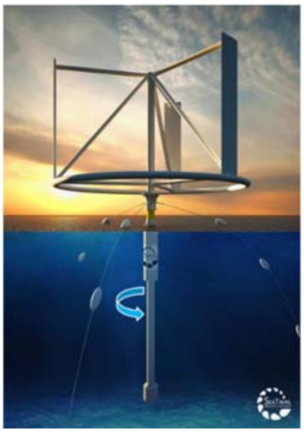
Classification:	Spar	Primary material:	Concrete/ steel hybrid
Depth range:	100m+	Moorings:	3 catenary
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	4
Full-scale prototype:	2013	Pre-commercial array:	TBC

Conventional spar-buoy with a slender body and deep draft, but a hybrid design in which the spar is split into a steel top section and concrete lower section. The use of heavier concrete material helps to lower the centre of gravity beneath the centre of buoyancy to stabilise the structure. Concrete also helps to reduce material costs and maximise local content. After an initial 100 kW prototype, a full-scale 2 MW unit was installed off Kabashima Island, Japan, in 2013, and has so far survived the severe typhoons which hit southern Japan. There are plans to build out the current site to 522 MW using 2 MW and scaled up 5 MW units.

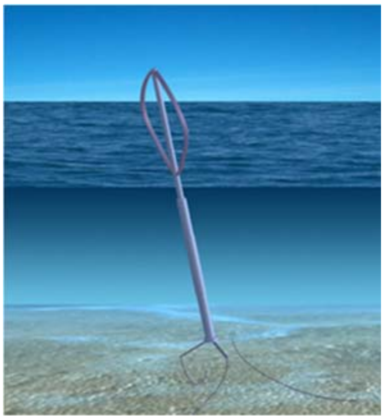
Advanced Spar — Japan Marine United

Classification:	Spar	Primary material:	Steel
Depth range:	80m+	Moorings:	3 catenary
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	Marubeni Corporation	TRL:	4
Full-scale prototype:	2013 (sub-station)	Pre-commercial array:	TBC

Alternative spar design with a shorter body to allow for more flexible application in shallower waters, using 'vacillation fins' to minimise sway and heave. The concept was chosen to support the world's first floating substation off the coast of Fukushima, installed in 2013, and it will support a 5 MW Hitachi turbine at the Fukushima site, expected in 2016.

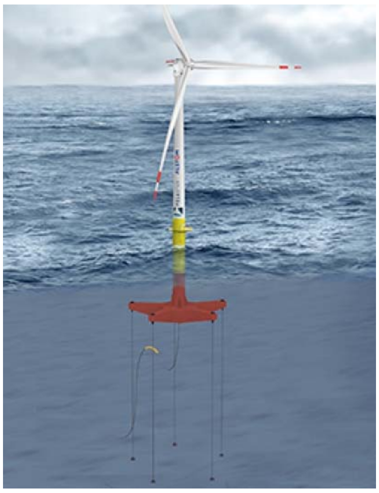
SeaTwirl	SeaTwirl Engineering			
	Classification:	Spar	Primary material:	Steel
	Depth range:	Undisclosed	Moorings:	Undisclosed
	Turbine axis:	Vertical	No. blades:	3
	Industrial partner(s):	-	TRL:	3
	Full-scale prototype:	TBC	Pre-commercial array:	TBC

SeaTwirl is a novel spar design that uses a vertical axis wind turbine to capture the wind energy and a torus ring stabilise the energy output. Only the generator and mooring system remains still as the entire structure spins, with the submerged floating body rotating in direct contact with the ocean water, thereby using the water as a roller bearing to function as a large low speed flywheel. This presents opportunities to reduce weight, for example by removing the need for a gearbox or roller bearings to take the weight of the turbine. A 1.5 kW prototype was installed in Swedish waters in 2014, with plans to scale up to 30 kW in 2015, before multi-megawatt demonstrations from 2017.

DeepWind Spar	DeepWind Consortium			
	Classification:	Spar	Primary material:	Steel
	Depth range:	Undisclosed	Moorings:	3 catenary
	Turbine axis:	Vertical	No. blades:	2
	Industrial partner(s):	-	TRL:	2
	Full-scale prototype:	TBC	Pre-commercial array:	TBC

The DeepWind spar is a novel floating wind concept consisting of a long vertical tube that rotates in the water using a vertical axis rotor and bottom-based generator. The structure is anchored to the seabed using a catenary mooring system. R&D support funding has been provided by the European Commission to advance the technology, with the potential for a 5 MW demonstrator.

2.4.3 Tension Leg Platforms

PelaStar	Glosten Associates			
	Classification:	TLP	Primary material:	Steel
	Depth range:	70-200m	Moorings:	5 taut-leg
	Turbine axis:	Horizontal	No. blades:	3
	Industrial partner(s):	Alstom	TRL:	3
	Full-scale prototype:	TBC	Pre-commercial array:	TBC

The Glosten PelaStar is a 5-arm submerged hull with a single central column, anchored to seabed with one cable tendon per arm. The low structural weight and modular design are major drivers for cost savings, with Glosten estimating a potential cost of energy of £85/MWh by the mid-2020s, if commercial deployments are achieved from 2020. The PelaStar was chosen by the ETI for a 6 MW demonstration at the WaveHub test site in Cornwall, supporting Alstom's 6 MW Haliade turbine. A FEED study has been completed, but the project was recently shelved due to planning and consenting delays at the site. Glosten Associates are now seeking alternative test sites to conduct the 6 MW demonstration by 2018.

Blue H TLP	Blue H Group			
	Classification:	TLP	Primary material:	Steel
	Depth range:	50-250m	Moorings:	3 taut-leg
	Turbine axis:	Horizontal	No. blades:	3
	Industrial partner(s):	-	TRL:	3
	Full-scale prototype:	2018	Pre-commercial array:	2020

Tension leg platform with a minimum of 3 taut-leg mooring lines, each connected to a gravity anchor system suitable for a range of seabed conditions. The turbine is located in the centre of a buoyant lightweight platform, which is semi-submerged during operation and held in position by the uplifting force and tension of the mooring tethers. An initial 80 kW prototype was installed off the coast of Italy in 2008, and the concept has since been refined to reduce structural mass. Blue H are currently seeking partners to finance and construct a full-scale proof-of-concept unit with a 5-7 MW turbine.

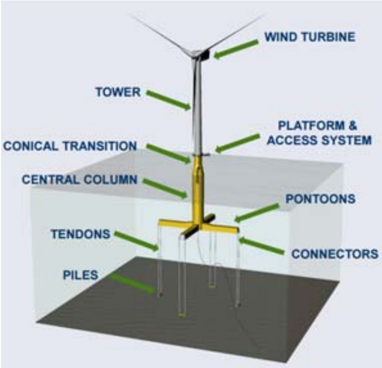
GICON-SOF	GICON		
Classification:	TLP	Primary material:	Steel
Depth range:	40-250m	Moorings:	8 taut-leg
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	2015	Pre-commercial array:	2017

The GICON® SOF (Schwimmendes Offshore Fundament, "Floating Offshore Foundation") is a TLP floating structure which has been developed by GICON in co-operation with renowned partners, such as TU Bergakademie Freiberg, Rostock University and Fraunhofer IWES. The TLP design consists of 4 linked columns anchored to the seabed with 4 vertical taut-leg mooring lines and an additional 4 support mooring lines to provide added stability that the designers anticipate to be equivalent to conventional fixed-bottom foundations. The modular design is also well-aligned to serial fabrication processes.

A series of successful tank tests has helped to optimise and de-risk the design for a full-scale demonstration, which is planned for 2015 in the German Baltic Sea. The pilot will enable significant monitoring of the structure's behaviour and further optimisation before commercial deployments from 2017.

Eco TLP	DBD Systems		
Classification:	TLP	Primary material:	Concrete
Depth range:	100m+	Moorings:	Undisclosed
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	2018	Pre-commercial array:	TBC

The Eco TLP is a concrete gravity anchor and floater coupled with taut tendons. The structure is fabricated using an economical slip-form process on a single 'Construction/Dry-Dock/Deployment' (CDD) barge, which is also used for installation, thereby removing the need for extensive port-side fabrication facilities. The use of concrete as the primary material can reduce material costs and the gravity anchor eases the stress usually associated with piled and suction anchors on TLP designs, whilst also facilitating an easier installation process. Tank testing has been completed and DBD Systems are now targeting a full-scale deployment at Dounreay Test Centre, off the north coast of Scotland.

TLPWind	Iberdrola		
			
Classification:	TLP	Primary material:	Steel
Depth range:	Undisclosed	Moorings:	4 taut (8 tendons)
Turbine axis:	Horizontal	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	TBC	Pre-commercial array:	TBC

Iberdrola's TLPWind concept consists of a central cylindrical column and four pontoons symmetrically distributed on its bottom. Each of the outer ends of the four pontoons incorporates porches which allow the connection of two tendons per pontoon, which provide a level of redundancy against potential tendon failures. At the top of the central column, a conical frustrum allows a smooth transition between the main cylinder and the wind turbine. The concept has performed well in tank testing and is now looking at further optimisations to the structure and bespoke installation vessel ahead of a potential deployment off the coast of Scotland by 2018.

Advanced Floating Turbine (AFT)	Nautica		
			
Classification:	TLP	Primary material:	Steel
Depth range:	40-700m	Moorings:	1 taut-leg
Turbine axis:	Horizontal	No. blades:	2
Industrial partner(s):	-	TRL:	2
Full-scale prototype:	TBC	Pre-commercial array:	TBC

Nautica's Advanced Floating Turbine (AFT) is a hybrid of TLP and semi-submersible characteristics. The tower and foundation outrigger arms enable the system to be transported to the installation site in a horizontal position before being raised to the operating position using a water ballast to erect the turbine. As water ballast is pumped into chambers in the platform, the change in weight and centre of mass causes the AFT to rotate from a horizontal position to the desired near-vertical position. A winch pulling on a guide cable provides additional tension to position the AFT system and mooring line into position at the anchor. This deployment methodology can be reversed to allow access for major work on the turbine. A 1:10 scale prototype is planned for 2016.

2.4.4 Multi-turbine and Hybrid Concepts

Hexicon	Hexicon			
	Classification:	Multi-turbine platform	Primary material:	Steel
	Depth range:	50-500m	Moorings:	8 catenary
	Turbine axis:	3 x Horizontal	No. blades:	3
	Industrial partner(s):	-	TRL:	2
	Full-scale prototype:	TBC	Pre-commercial array:	TBC

The Hexicon multi-turbine platform consists of a series of buoyancy columns distributed in a large truss structure. Three of the columns carry conventional towers and turbines, which is anticipated to provide material and cost savings versus stand-alone concepts. The structure is catenary moored and the mooring system is used both for station keeping and for aligning the platform with wind direction. This ability to turn the platform gives each turbine free and linear wind to avoid wakes losses. The design has undergone detailed numerical modelling and is now planning scaled testing to further optimise the design before a full-scale demonstration towards the end of the decade.

WindSea	FORCE Technology			
	Classification:	Multi-turbine platform	Primary material:	Steel
	Depth range:	50-120m	Moorings:	3 catenary
	Turbine axis:	3 x Horizontal	No. blades:	3
	Industrial partner(s):	-	TRL:	2
	Full-scale prototype:	TBC	Pre-commercial array:	TBC

Semi-submersible multi-turbine platform with three vertical columns connected by a ring pontoon at the bottom and by box girders at the top. Each column supports a turbine, two upwind and one downwind, with the towers inclinated such that the relative position of the turbines minimises wake losses. The designers are targeting early application for the concept to supply power to offshore oil platforms, with commercial-scale power production beyond 2020.

W2Power	W2Power			
	Classification:	Multi-turbine hybrid wind-wave platform	Primary material:	Steel
	Depth range:	Undisclosed	Moorings:	Undisclosed
	Turbine axis:	2 x Horizontal	No. blades:	3
	Industrial partner(s):	-	TRL:	2
	Full-scale prototype:	TBC	Pre-commercial array:	TBC

Hybrid wind & wave energy conversion plant in which two corners of the triangle support one wind turbine each and the third corner houses the power take-off for the wave energy conversion system. The wave energy device uses a conventional Pelton turbine driven by three lines of wave-actuated hydraulic pumps mounted on the platform's sides to reach a total unit capacity of up to 10 MW, if two 3.6 MW turbines are used.

Poseidon P80	Floating Power Plant			
	Classification:	Hybrid wind-wave platform	Primary material:	Steel
	Depth range:	45-200m	Moorings:	5 catenary
	Turbine axis:	Horizontal	No. blades:	3
	Industrial partner(s):	-	TRL:	3
	Full-scale prototype:	TBC	Pre-commercial array:	TBC

Poseidon is a triangular semi-submersible structure with a centrally placed wind turbine, integrated with four wave power units, rated at 400-650 kWh each. Total capacity can therefore reach up to 7.6 MW if a 5 MW wind turbine is supported. A turret mooring system is used, which allows the structure to passively rotate up to 260 degrees to face the incoming waves. A 1:2.3 scale structure (P37) was installed in 2010, supporting 3 turbines with a total capacity of 0.03 MW.

SKWID — MODEC

Classification:	Hybrid wind-wave platform	Primary material:	Steel
Depth range:	Undisclosed	Moorings:	Undisclosed
Turbine axis:	VAWT	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	2015	Pre-commercial array:	TBC

Hybrid wind & wave device which uses a vertical axis turbine that is claimed to be able to capture twice as much energy as similar onshore turbines. The full-scale structure supports a 500kW vertical axis turbine and is stabilised by the ballast from the weight of the marine current turbines underneath, which lowers the centre of gravity in much the same way as spar-buoy designs. The manufacturers hope to eventually lease the SKWID (Savonius Keel & Wind Turbine Darrieus) to fishing co-operatives on the western coast of Kyushu and the device could also provide electricity to remote islands. Two pilot demonstrations have been delayed after a key component sank in 2013 and the entire device sank in 2014.

WindLens — Riam/Kyushu University

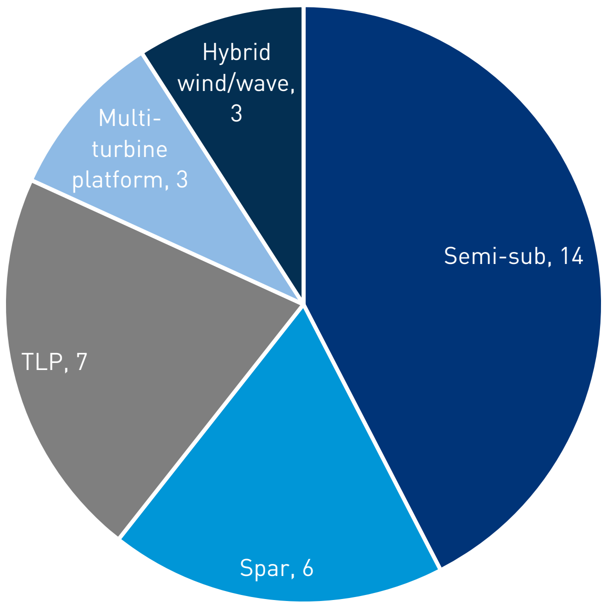
Classification:	Multi-turbine platform	Primary material:	Steel
Depth range:	Undisclosed	Moorings:	Undisclosed
Turbine axis:	2 x Horizontal axis wind lens per unit	No. blades:	3
Industrial partner(s):	-	TRL:	3
Full-scale prototype:	TBC	Pre-commercial array:	TBC

Semi-submersible multi-turbine platform which consists of a series of hexagonal platforms each supporting two WindLens turbines and covered in solar PV panels. A prototype model with two 3kW turbines was launched in December 2011 for a one year trial and a larger model with 250kW and 300kW turbines is currently under development.

2.5 Market Analysis

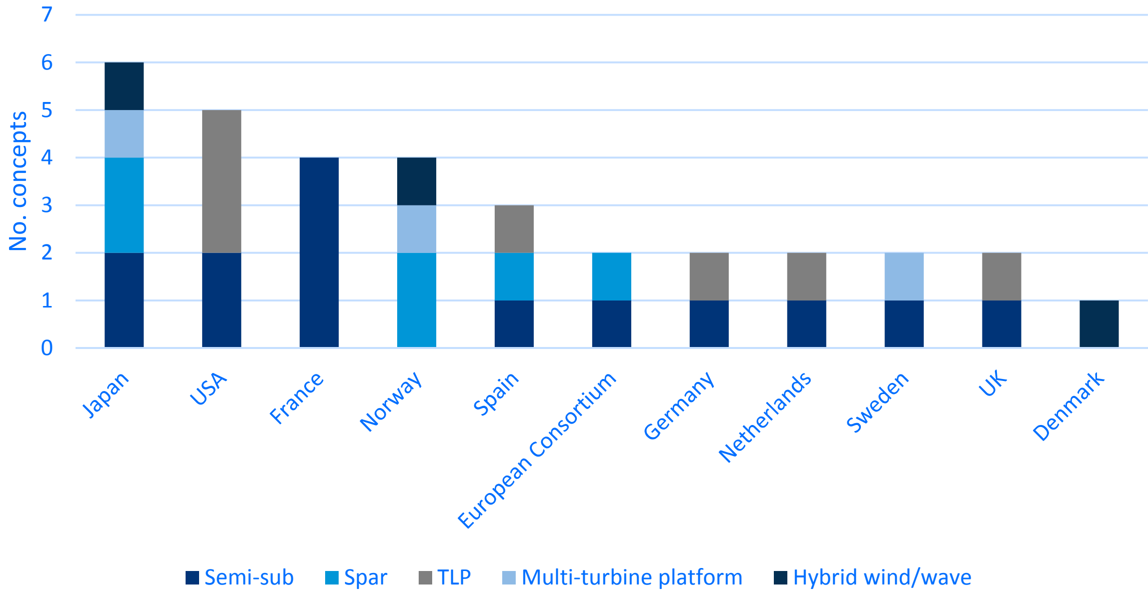
Thirty three concepts have been identified in the market from 11 different countries. These constitute concepts that have openly published material on their design, and there may be more concepts currently under development that have not been captured in this market analysis. The majority of concepts assessed are semi-submersibles, likely due to the flexibility of their application to site locations with shallow water depths and the lower infrastructural requirements for installation. The more site constrained TLPs and spars are also well represented, with a handful of multi-turbine platforms and hybrid wind/wave devices also under development (figure 2.5.1).

Figure 2.5.1. Typologies under development



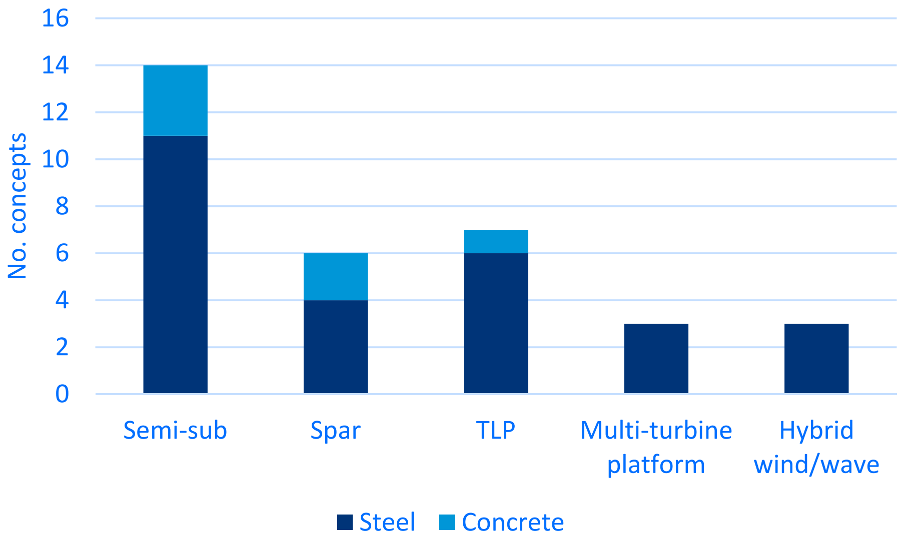
By region, Europe leads the way in device development, representing two-thirds of the concepts on the market; however, by country, Japan has the greatest number of concepts, followed closely by the USA (figure 2.5.2). There is also a discernible trend in the typologies developed by different countries. The flexible application of semi-submersibles means that they are a popular choice for development in most markets, with France in particular targeting semi-submersible concepts that can be deployed in shallower waters. Conversely, spar-buoys are generally limited to geographies where very deep water is prevalent; namely, in Japan and Norway. Meanwhile, TLP designs have principally emanated from the USA, as well as in a handful of European countries.

Figure 2.5.2. Geographical origin and typology of floating wind concepts



Steel is the dominant material used in foundation designs (figure 2.5.3), mirroring the fixed-bottom offshore wind foundation market. However, a number of concepts have adopted concrete as the primary material. Despite the significantly heavier mass, concrete can be over ten times cheaper and significantly less volatile than steel. Dependent on the design, this can lead to a net cost saving, as well as provide benefits for high local content and ease of fabrication. However, it should be stressed that the cost benefit of designs and the materials used will change on a concept-by-concept basis. A quantitative analysis of steel vs. concrete designs is included in section 3.

Figure 2.5.3. Primary material of floating platforms



2.6 Design Standards for Floating Structures

With early stage technologies, such as floating wind, designers and developers are often unwilling to divulge commercially sensitive information about lessons learned or challenges. However, as the technology develops, this problem can be circumvented by the introduction of industry guidelines and standards. DNV-GL have developed a standard for the design of floating wind turbine structures, DNV-OS-J103, through an international joint industry project running from 2011 to 2013, which included the participation of key players in the floating wind industry, such as Statoil, Principle Power, Glosten Associates, Alstom, Gamesa, Sasebo Heavy Industries, Nippon Steel & Sumitomo Metal, STX Offshore & Shipbuilding, Iberdrola, and Navantia.

The standard, which is to be used in conjunction with the fixed structures counterpart, DNV-OS-J101, used data from operational and planned demonstration projects – Hywind, Pelastar, and WindFloat – to produce a set of principles, technical requirements, and guidance for the design, construction and in-service inspection of floating wind turbines. Transportation, installation, and inspection issues are taken into account to the extent necessary in the context of structural design structures, and special provisions are made for different floater types, building on existing design standards from the oil & gas industry; for example on offshore structures (DNV-OS-C101), tendons (DNV-OS-C105), and mooring lines (DNV-OS-E301).

Technical issues covered in the DNV-GL floating wind standard (DNV-OS-J103) include:

- Safety philosophy and design principles
- Site conditions, loads and response
- Materials and corrosion protection
- Structural design
- Design of anchor foundations
- Station keeping
- Floating stability
- Control system
- Mechanical system
- Transport and installation
- In-service inspection, maintenance and monitoring
- Cable design (structural)
- Guidance for coupled analysis (appendix)

Additional standards and best practice guidelines are currently being scoped through different JIPs, and there are plans to update the existing standards when more data would be available.

While DNV-GL standards have been dominant in Europe, the American Bureau of Shipping (ABS) have developed a similar set of guidelines which have been adhered to by concept designers in the United States. The document provides guidance on the design, construction, and installation of floating wind structures, addressing all aspects of the structure apart from the RNA (rotor nacelle assembly).

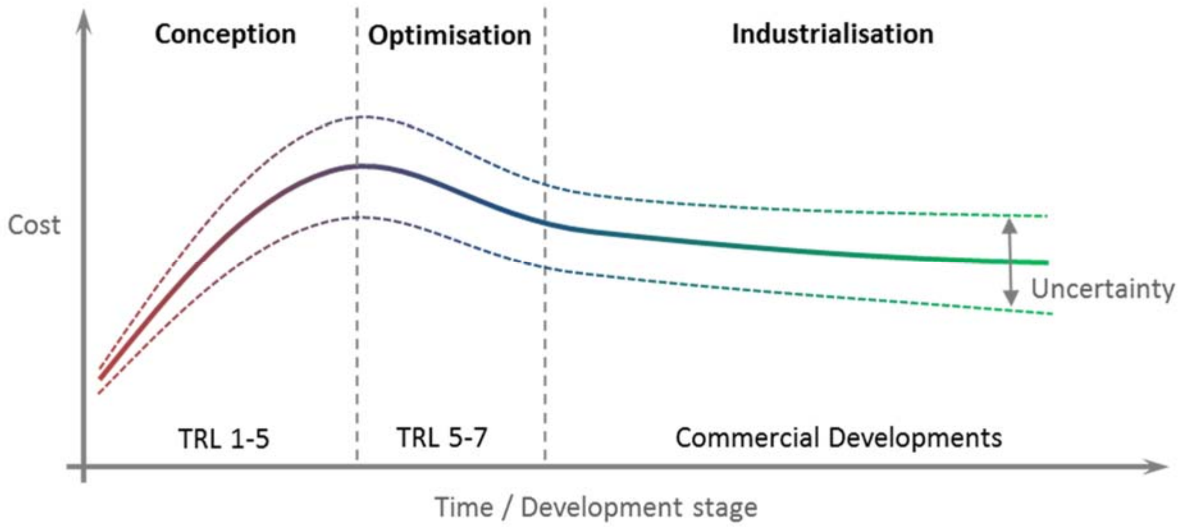
2.7 Cost Competitiveness of Floating Wind

Floating wind technology is in its infancy and therefore currently has high costs, particularly for early prototype and pre-commercial arrays. However, early prototypes do not reflect the true costs that can be expected with mass deployment, once designs have been optimised to reduce structural weight, introduce novel component technologies, improve installation methods, adopt serial fabrication processes, and benefit from scale effects more generally. There is therefore significant potential for costs to come down to reach parity with fixed-bottom offshore wind when deployed at scale.

It should be highlighted, though, that while fixed-bottom and floating wind foundations are comparable to some extent in sites with depths that could host both concepts (i.e. depths ranging from approximately 40m to 60m), it is more likely that floating wind will be used to exploit deeper waters (>60m), which are not suitable for fixed-bottom structures. This could facilitate the development of more sites closer to shore, avoiding the need to develop shallow sites far from shore, which create challenges for electrical transmission, installation, and O&M.

In addition, the reader should note that the references and comparisons outlined in this section rely on existing publicly available data. On this basis it should be noted that while cost data for fixed-bottom foundations are fairly robust, cost data from floating wind foundations have not been validated and carry greater uncertainty. Experience from The Carbon Trust has shown that cost figures from new and innovative technologies tend to increase from initial conception to detailed development and then decrease when the concept is optimised and industrialised (figure 2.7.1). As a technology at the early stages of development, the CAPEX and LCOE estimates for floating wind may underestimate the full costs of deploying the technology. This has already been evident in demonstrations at the Fukushima FORWARD project in Japan, which has ran over budget and is struggling to meet its cost targets.

Figure 2.7.1. Technology cost evolution through time



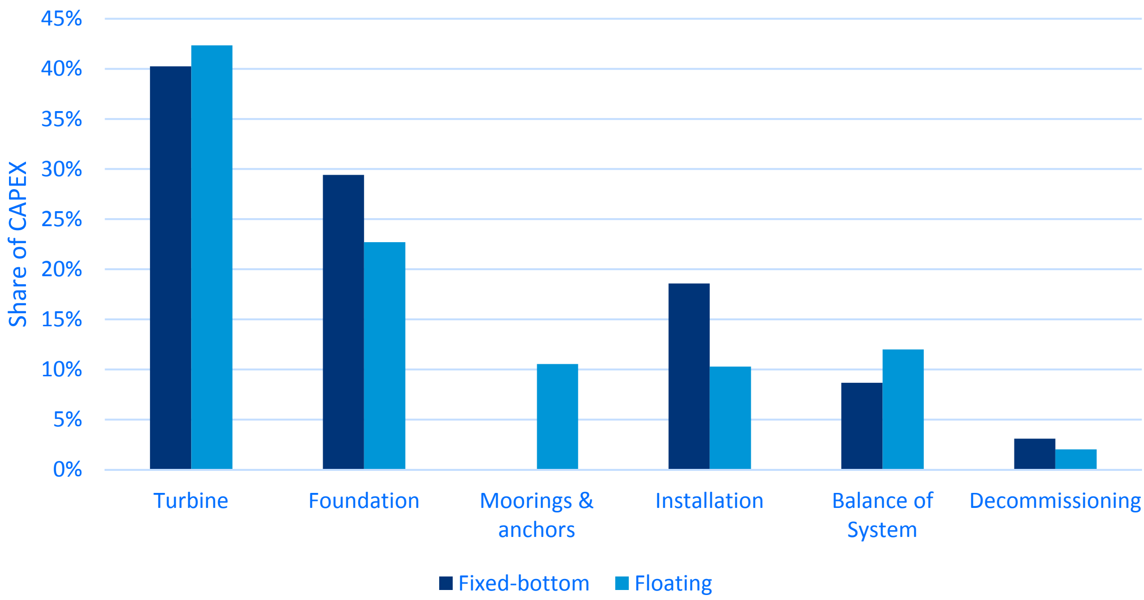
N.B. TRL definitions can be found in table 4.1.1.

The following sections consider the cost competitiveness of floating wind versus conventional fixed-bottom structures. Section 3.5 will assess the cost breakdown of floating wind in more detail, but will not be used for a cost comparison with fixed-bottom offshore wind.

2.7.1 Capital Expenditure (CAPEX)

A breakdown of the typical capital expenditure (CAPEX) for a fixed-bottom and floating wind farm is detailed below (figure 2.7.2). The exact breakdown will vary on a project-by-project basis, depending on the site conditions and technologies adopted, but the figures below provide a general indication for illustrative purposes.

Figure 2.7.2. Cost breakdown for typical fixed-bottom and floating offshore wind projects



Like conventional fixed-bottom projects, the cost of the turbine dominates the capital expenditure for floating wind. The majority of floating wind concepts claim to be 'turbine agnostic' and able to support most conventional offshore turbines, hence the similar costs incurred. However, after consultation with industry experts (modelling and OEM specialists), it is considered that a 'turbine agnostic' solution may not be optimal, and detailed match-making and tuning between the wind turbine generator and the foundation will need to be developed to reach the most cost-effective solutions. Turbine design modifications, though minor, could therefore increase turbine costs for floating wind projects.

For deep water sites (beyond ~45m), foundation costs can be expected to be lower for floating wind projects, largely due to the lower structural mass and material costs compared to fixed-bottom deep water structures. However, once the cost of the moorings and anchors is included, the cost is expected to exceed that of fixed-bottom foundations.

Balance of system is also expected to be higher for floating wind projects. This is largely due to the need for a floating substation and dynamic cables, which are both less established technologies that are more expensive than the equivalent transmission methods used for fixed-bottom projects.

However, where floating wind can deliver significant cost savings is in installation. Namely, the ability to assemble the turbine onshore and tow the fully assembled structure to site primarily using simple tug boats removes the need for expensive heavy lift jack-up and dynamic positioning vessels, for both foundation installation and offshore turbine assembly. Charter day rates can be around 4-8 times lower for the vessels required to install floating wind structures, in addition to dramatically lower mobilisation costs, resulting in significant CAPEX savings (table 2.7.1). The towing of fully assembled structures to site can also be conducted in more challenging met-ocean conditions, which can extend the weather window for installation compared to the more benign conditions required for offshore turbine assembly with fixed-bottom wind farms, imposed by jack-up vessel limitations. Another added benefit is the lack of piling noise, which can ease the consenting process and remove the need for noise mitigation technologies. However, it should be noted that the installation process for floating wind structures needs further refinement and optimisation, although this is expected to be achieved with increasing deployment towards commercial scale.

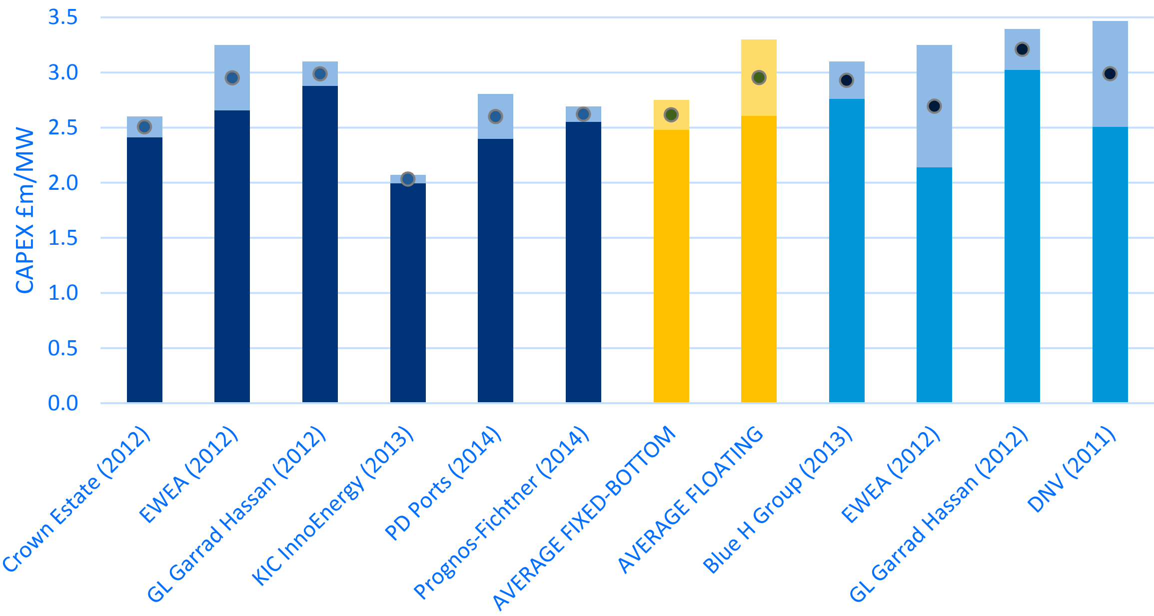
Table 2.7.1 Typical charter day rates for installation vessels (GL Garrad Hassan, 2012)

Fixed-bottom installations		Floating wind installations	
Vessel	Day rate	Vessel	Day rate
Heavy lift vessel (foundation installation)	€150k-500k	Standard tug boat (tow out and hook up)	€30k-60k
Jack-up vessel (turbine installation)	€150k-200k	Anchor handling tug (mooring installation)	€20k-50k
Mobilisation	Several M€	Mobilisation	€<100k

Though only a relatively small share of total CAPEX, floating wind can also offer benefits in decommissioning. While fixed-bottom foundations require specialised equipment and vessels to decommission (with budget set aside from the beginning of the project), for floating wind this is far simpler. Once the anchors are removed, or moorings are cut, the full structure can be towed back to shore, at significantly lower cost. It is worth noting that some experts are currently stating that fixed bottom decommissioning is likely to cost more than initially expected.

The net effect of these cost variations is difficult to analyse given the lack of operational floating wind projects, and therefore the uncertainties that exist. The few prototypes installed to date are a poor reference for the cost of a commercial project, but a handful of studies have attempted to derive cost estimates for commercial-scale floating projects. Figure 2.7.3 presents a summary of the outcomes, and compares them to similar studies for fixed-bottom offshore wind. It should be noted that each of the cost estimates carry their own assumptions, and these assumptions will vary significantly between sources with regard to wind farm capacity, turbine capacity, site conditions (e.g. water depth, distance from shore), and year of commissioning; however, the sources do broadly correspond to commercial-scale projects during the early 2020s. Given the importance of site conditions and number of variables involved, an accurate cost comparison can only be truly achieved on a project-by-project basis.

Figure 2.7.3. CAPEX estimates for fixed-bottom and floating wind



The data indicates that fixed-bottom technology is expected to derive lower capital expenditure than floating wind projects. This is largely driven by the higher combined cost of the foundation and mooring & anchoring system. Despite cost savings during installation, the net effect is a higher total CAPEX. However, as water depth increases, the cost competitiveness of floating wind would be expected to improve exponentially, since cost increases with greater depth would be marginal. In shallow water depths (< 100m), the cost of the mooring and anchoring system is likely to be more expensive due to the challenges of forming a proper catenary configuration, but as water depth increases from 50m to 100m, the additional capital cost of longer mooring lines will likely be negated somewhat by a smaller platform size. The 80-120m depth range is expected to be optimal for most floating wind solutions, though cost increases beyond 120m would be small and could be offset against higher yield if areas with strong wind resource can be exploited.

2.7.2 Operational Expenditure (OPEX)

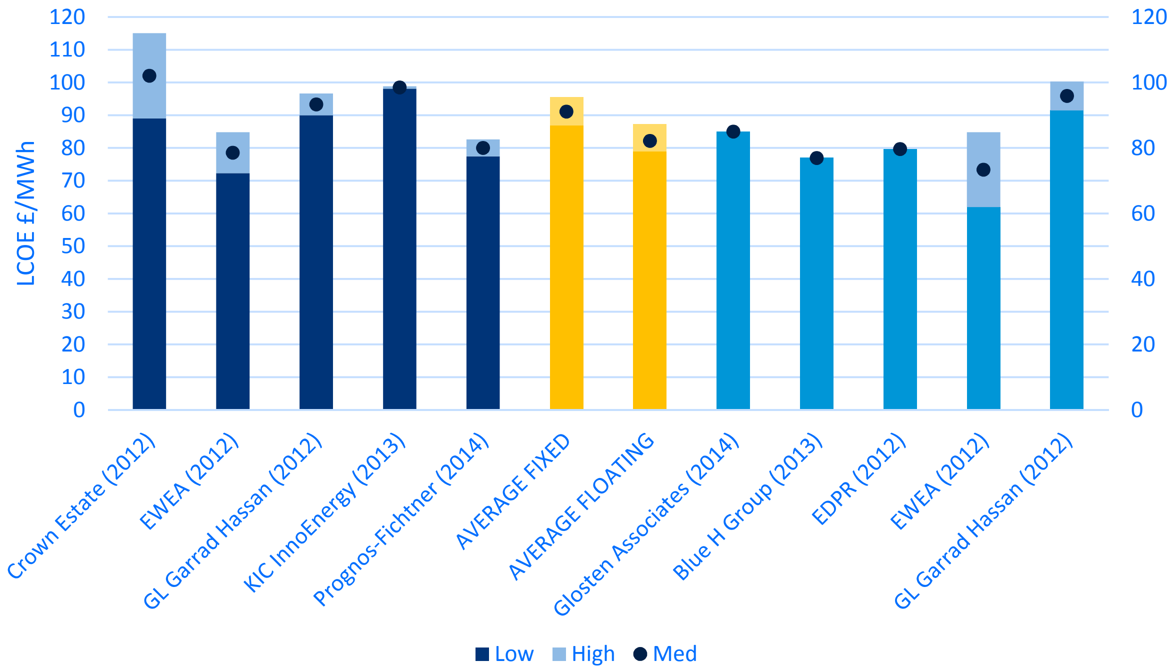
Despite the anticipated higher CAPEX for floating wind, another key driver of cost savings versus fixed-bottom projects is reduced operational expenditure (OPEX). While the cost of minor repairs is expected to be similar for both fixed-bottom and floating projects, with analogous technician access by crew transfer vessel for each, there are expected cost savings for major repairs, such as gearbox replacement, which can represent 35-50% of total OPEX for offshore wind farms (GL Garrad Hassan, 2012). Whereas major repairs for fixed-bottom turbines require expensive jack-up or dynamic positioning vessels, most floating wind structures are designed such that they can be disconnected from their moorings and towed back to shore to conduct repairs at port. While disconnecting and towing the full structure to and from site can be a slower repair process, this is balanced by the rapid mobilisation of standard tug boats. With fixed-bottom wind farms the opposite is expected, with longer mobilisation timeframes but rapid repairs once available. The net impact is likely to result in a similar level of downtime, and associated lost revenue, for each. However, the reduced charter rates and mobilisation costs for standard tug boats and the lower weather dependency for repairs are expected to lead to a net reduction in operational expenditure for floating wind farms. Although it should be noted that the cost benefit will be heavily influenced by site conditions, particularly in relation to distance from shore and met-ocean conditions.

2.7.3 Levelised Cost of Energy (LCOE)

Comparing the levelised cost of energy (LCOE), and thus the cost competitiveness, of floating wind with conventional fixed-bottom wind farms must consider a combination of the CAPEX and OPEX documented above, together with the expected energy output of the respective wind farms. While CAPEX has been shown to be considered slightly higher for floating wind, OPEX is expected to be lower. Energy output will be variable and site dependent; however, the greater flexibility of floating wind and ability to potentially access higher wind speeds at deep water locations unsuitable for fixed-bottom foundations could improve its cost competitiveness. Early demonstrations appear to confirm the potential for floating turbines to capture high yield, with Statoil's 2.3 MW Hywind demonstrator attaining capacity factors of ~50%, compared with ~40% average for fixed offshore turbines and 25-30% onshore (Statoil, 2014). However, yield will also be influenced by the level of wake effects in the wind farm, which has so far had little attention in the context of floating wind.

As per the CAPEX data outlined above, attempts have been made to estimate the likely LCOE for commercial floating wind farms. Figure 2.7.4, below, presents a summary of LCOE estimates for both fixed-bottom and floating offshore wind. Again, each estimate has its own set of assumptions which vary by source, although they do broadly correspond to commercial-scale projects in the early 2020s.

Figure 2.7.4. Levelised cost of energy (LCOE) estimates for fixed-bottom and floating wind



From the data observed above, it can be seen that the expected LCOE of commercial-scale fixed-bottom and floating wind projects are comparable, though slightly lower for floating wind. While it should be re-enforced that caution should be taken when analysing such data, particularly when comparing data points of one technology which has been deployed at scale and another which is still at the demonstration stage, it is evident that floating wind can be considered to hold the potential to be cost competitive with fixed-bottom offshore wind.

Studies carried out by the Energy Technology Institute (2015) have defined two scenarios to reach a low carbon energy mix in the UK, the 'Clockwork' scenario (low carbon investments coordinated at a national level) and the 'Patchwork' scenario (energy strategies developed at a regional level), which expects that offshore wind installed capacity in the UK by 2050 could reach up to 50 GW or 20 GW, respectively. In the lower limit scenario, the ETI expects that no floating wind would be developed at a commercial scale due to its higher lifecycle costs (considering current estimates), since the development of sites is likely to be concentrated in near-shore shallow areas (i.e. below ~45m). However, at higher deployment scenarios for offshore wind, floating wind is expected to play a more significant role by accessing near-shore deep water sites that would reduce the need to develop more expensive far-shore sites, resulting in lower overall deployment costs for offshore wind. However, this outlook highlights the need for floating offshore wind to demonstrate attractive LCOE values in order to be competitive against sites where fixed-bottom foundations can be installed.

It should be noted that the analysis and discussion above is given in the context of the UK. The cost competitiveness of floating wind will vary by market, depending on the prevailing site conditions, local capabilities and dependencies, and the broader energy mix. Thus, while floating wind may not be attractive to some markets, it may well still be deployed at a commercial scale in others.

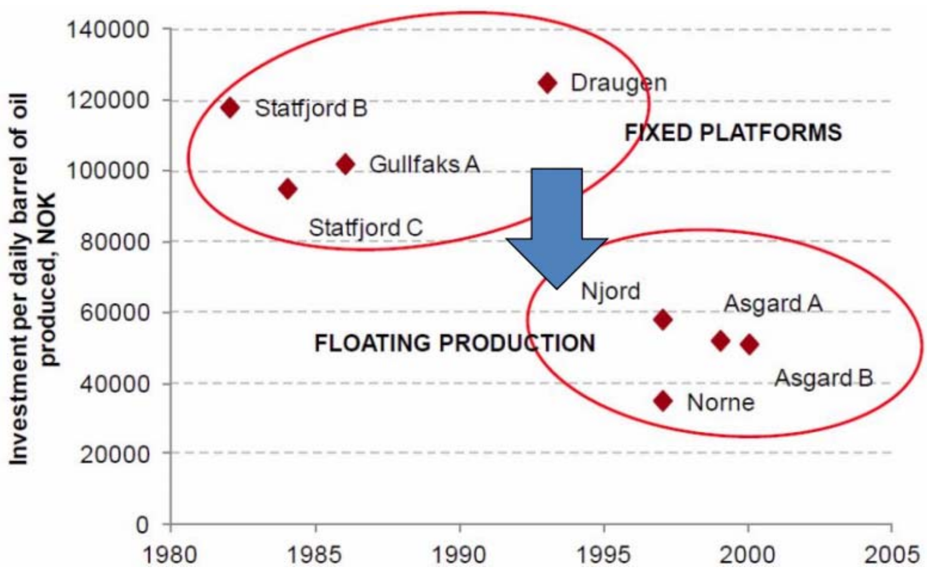
2.7.4 Cost Reduction Potential

The Energy Technologies Institute (2013) suggest that the levelised cost of energy for offshore wind needs to reach ~£85/MWh by 2030 in order to play a major role in the UK's energy mix up to and beyond 2050. For floating wind, this presents a time pressure to demonstrate the technologies before 2020 in order to begin scaling up deployment and deliver the cost reductions necessary in the period from 2020 to 2030. The cost estimates highlighted above appear to confirm that floating wind can reach cost parity with conventional fixed-bottom offshore wind and reach the £85/MWh mark, but scaled deployment is key to unlocking the cost savings required, largely through:

- Technology improvements & design optimisation – reduce structural mass; develop modular designs suitable for serial fabrication; optimise mooring and anchoring systems; integrated turbine-foundation design to improve overall performance; optimise installation process
- Learning effects – learning by doing as deployment increases
- Market size – full cost reduction potential cannot be realised until the production volume is sufficient to mature the supply chain
- Supply chain improvements – building a robust supply chain with competition in the market to drive down costs; developing optimised fabrication lines; improving port facilities to cater for the needs of floating wind installations
- Design standardisation – unlike fixed structures, floating platforms are less constrained by water depth and seabed conditions, allowing for cost savings through standardisation and mass production
- Increasing yield – flexibility to site location enables access to areas with better wind resource than might be possible with fixed-bottom turbines

The desired cost reduction in offshore wind has already been demonstrated in the oil and gas industry, with the move from fixed to floating platforms leading to reduced costs per daily barrel of oil produced (figure 2.7.5). Cost savings were achieved through more standardised designs, optimised fabrication lines, easier assembly, transportation, and installation, and easier decommissioning. The same principles are also applicable to offshore wind, and just as floating oil platforms managed to improve cost competitiveness by accessing greater oil reserves, it is expected that floating offshore wind could achieve further efficiencies by accessing stronger and more reliable wind resource. Although this will ultimately depend on the level of build-out for offshore wind over the coming decades as cheaper near-shore shallow sites for fixed-bottom structures are exhausted.

Figure 2.7.5 Improved cost efficiencies in North Sea oil production using floating platforms (The Crown Estate, 2014)



Yet it should be acknowledged that there are good prospects for significant cost reduction in fixed-bottom offshore wind over the next 5-10 years, a more mature technology which has a head start over floating wind. Data from The Crown Estate (2012), Prognos-Fitchner (2014), and other sources quantify this reduction at ~20-40% from the beginning of the decade. Thus cost reduction in floating will need to be accelerated to not just keep pace but exceed the rate of cost reduction in fixed-bottom offshore wind if it is to reach cost parity in time to be considered to play a major role in the UK's future energy mix.

The cost reduction potential for floating wind is evident, but the rate at which it will be achieved to reach parity with fixed-bottom offshore wind, and the ultimate cost level that can be attained, is dependent on public and private support to reach the volumes necessary to benefit from scale effects. To realise the cost reduction potential of floating wind it is therefore critical for ongoing support to be provided to prove the technologies, optimise designs, identify further opportunities for cost reduction, and begin scaling up deployment towards 2020 and beyond. This will require a secure and stable regulatory framework, sufficient RD&D financing to support innovation, and targeted RD&D programmes to overcome common industry challenges.

2.8 Government Support for Floating Wind

The high cost of demonstration projects for floating wind means that existing support subsidies for commercial fixed-bottom offshore wind projects are insufficient to provide a suitable return on investment, and given the nascent state of floating wind technology, it is unsurprising that there are few targeted subsidy mechanisms in place to support floating wind projects. To date, government support has primarily consisted of grants to support research and development activities, together with a few notable demonstration projects which have received public funding. Details of the most active national governments supporting floating wind technology is provided below.

Europe

Scotland

Scotland is currently the only country to offer a subsidy support mechanism for floating wind. Designed to encourage the development of floating wind pilot projects, the Scottish Government have offered 3.5 Renewable Obligation Certificates (ROCs) per MWh[6], which is 1.5 ROCs higher than that currently received by fixed-bottom offshore wind farms. However, as yet, no projects have managed to develop projects to take advantage of this level of support, and with the Renewable Obligation set to expire in October 2018, a number of developers are racing to secure sites and contracts for pilot projects. The most advanced project to secure Scottish ROCs is Statoil's Hywind Scotland Pilot Park, a 30 MW array off the coast of Peterhead on Scotland's east coast, which is targeting commissioning in 2017. Two further pre-commercial arrays in Dounreay (30 MW – north coast of Scotland) and Kincardine (50 MW – east coast of Scotland) are aiming to come online by 2018. For more details on these projects, see section 2.9.1.

A successor subsidy mechanism to the Scottish ROCs has not been announced. The incoming Contracts for Difference (CfD) regime does not include an increased subsidy or designated allocation for floating wind, which means that floating wind projects will need to compete with fixed-bottom offshore wind and other 'less established technologies' in Pot 2 of the CfD auction process. The UK and Scottish Government could consider a ring-fenced CfD pot for floating wind going forward, as used with wave and tidal technology, or simply capital grants to support full-scale demonstrations. In the absence of a support mechanism it is unlikely that floating wind projects will be developed in Scotland beyond 2018, with developers turning their focus to other, more attractive markets.

Other UK

While the UK Government considered floating wind technology to be too nascent to merit higher subsidy under the Renewable Obligation, the UK has supported floating wind technology through the Energy Technologies Institute, which commissioned a £25m offshore wind floating system demonstrator (N.B. ETI funding comes from both public and private sources). The chosen concept,

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[6] The value of ROCs is dictated by auction, but typically ranges from £40-50 per MWh. Assuming a wholesale price of electricity of ~£45/MWh, a floating wind project developer can expected to receive ~£200/MWh for their project.

Glosten's PelaStar tension leg platform, has undergone a detailed FEED (front end engineering and design) study but the planned 6 MW deployment at the WaveHub site off the coast of Cornwall was recently cancelled due to consenting delays. The UK Government has also provided a small amount of support through the DECC Offshore Wind Component Technologies Scheme, which has supported the TetraFloat concept. However, the focus for DECC appears to be on fixed-bottom floating wind.

In April 2012, the UK and USA signed an agreement to collaborate on the development of floating wind technology, as part of a broader Memorandum of Understanding on 'Collaboration in Energy Related Fields'.

France

Despite no deployment of fixed-bottom offshore wind to date, France is actively pressing ahead with plans to develop floating wind technology. In December 2014 the French Government announced plans for a call for an expression of interest for floating offshore wind systems, which is expected in June 2015. The funding from the Investment Program for the Future (PIA) will provide floating projects with up to €150m, but the number and capacity of the projects has yet to be disclosed. At least three French consortia are expected to participate in the call, including a prototype of Ideol's concrete semi-sub with a 2 MW Gamesa turbine, a prototype of EDF and Nenuphar's Vertiwind semi-submersible platform with a 2 MW vertical axis turbine, and a full-scale demonstration of DCNS' SeaReed semi-submersible concept, supporting Alstom's 6 MW Haliade machine.

Norway

Given the extensive deep water locations surrounding Norway, the Norwegian Government has also been keen to support the development of floating wind. Public body Enova provided a grant of NOK 59 million (~£5 million) for Statoil's 2.3 MW Hywind demonstration and the Research Council of Norway has provided funding support for the Sway concept.

Portugal

Building on the successful 2 MW demonstration of Principle Power's WindFloat device in 2011, the Portuguese Government have awarded a €19m grant to support the development of a 27 MW extension off the coast of Aguçadoura. The project will also receive funding from the European Commission (see below).

European Commission

The majority of funding for existing research, development, and demonstration (RD&D) activities in Europe has been provided by the European Commission, largely through the Seventh Framework Programme (FP7) and NER 300. FP7 supported the 2 MW demonstration of Principle Power's WindFloat semi-sub off the coast of Portugal, and has provided the seed funding for a number of devices that are now gaining interest with industrial backers (e.g. VERTIWIND, IDEOL); meanwhile NER 300 will provide €30 million to Principle Power to develop a 27 MW project off the coast of Portugal. Future funding from the European Commission can be sought from two major funding pots, Horizon 2020 and DemoWind, which include calls for the demonstration of deep water offshore wind technologies. More information on the European Commission's RD&D programmes can be found in section 2.9.2.

Japan

Japan has been conducting research in floating technology for the past 20 years, establishing itself as a world leader in this area. However, it is only since the Fukushima nuclear disaster in 2011 that concerted efforts have been focussed on developing floating wind power. Historically reliant on nuclear energy for a large proportion of its electricity, the closure of most of the country's nuclear plants in the wake of the disaster has stimulated significant interest in renewable technologies, including offshore wind. Surrounded by deep water, Japan is constrained by how much fixed-bottom offshore wind can be installed, but the proximity of deep water locations makes it the ideal location for floating wind turbines.

Since 2011 the Japanese Government have therefore invested heavily in research, development, and demonstration activities, including the iconic Fukushima FORWARD Floating Offshore Wind Farm Demonstration Project (FORWARD), which has aspirations to eventually reach up to 1 GW in capacity. The Japanese Ministry of Economy, Trade, and Industry (METI) has invested a staggering 53 billion yen (~£292 million) in the Fukushima project, the first phase of which included the installation of a 2 MW floating turbine and the world's first floating substation, with Phase 2 expected to see the installation of 7 MW and 5 MW turbines in 2015 and 2016, respectively.

Meanwhile, the Japanese Ministry of the Environment (MOE) provided a grant of 6 billion yen (~£33 million) to install a hybrid concrete-steel spar buoy at Kabashima, in the Goto Islands. The project includes a work stream focussing the environmental impact of floating wind turbines. The MOE have also recently announced plans to fund a detailed environmental impact assessment for a 522 MW project in the Goto Islands.

USA

The US is another potentially large market for floating wind, particularly along the west coast, where deep waters preclude the use of fixed-bottom foundations. The US Department of Energy (DOE) has issued a $47 million grant to Principle Power to develop a 30 MW pre-commercial array off the coast of Oregon, consisting of five 6 MW turbines on the WindFloat semi-submersible concept, which has had a 2 MW prototype in operation of the coast of Portugal since 2011.

The US Government have also been supporting floating wind on the East Coast. The DOE granted $12 million over a 5 year period to DeepCWind, a consortium based at the University of Maine, which in 2013 installed a 1:8 scale prototype demonstration of the VolturnUS floating system, the USA's first offshore wind turbine and the world's first concrete-composite floating wind platform. Subsequent to this, the DOE have provided an additional $4 million grant towards a FEED study for two full-scale 6 MW units. The project missed out on DOE funding for the construction of the demonstration, but the University of Maine are still confident of reaching financial close and achieving commissioning by 2018.

As noted above, the US has also entered into an agreement with the UK to collaborate on initiatives to develop floating wind technology.

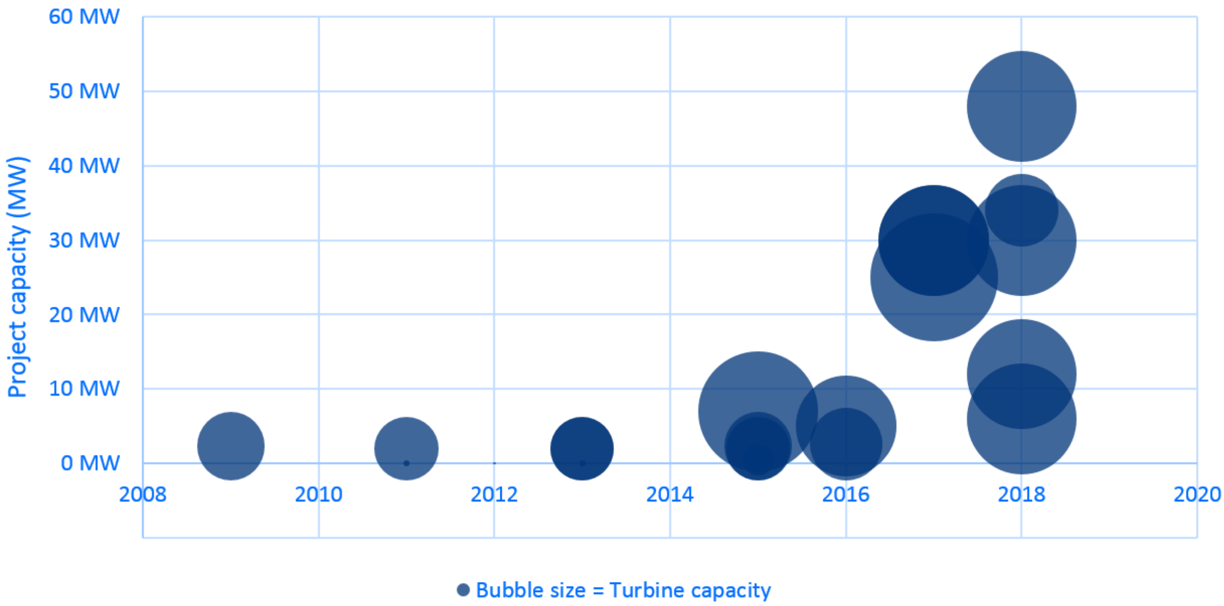
Details of all publically funded research, development, and demonstration initiatives can be found in section 2.9.

2.9 Research, Development and Demonstration Initiatives

2.9.1 Operational and Planned Floating Wind Projects

Following a handful of successful full-scale demonstrations, the scale of floating wind projects is beginning to increase as concepts prepare for commercial deployment, both in terms of total project capacity and turbine rating (figure 2.9.1). For concepts such as Hywind and WindFloat, this is a natural progression from their single prototype demonstrations of ~2 MW towards pre-commercial arrays using 6 MW units. A number of concepts are likely to follow this path, with single prototype demonstrations planned for 2015-2018 (e.g. GICON-SOF, Vertiwind, IDEOL, SeaReed). Further details on the projects under development can be found below and in table 2.9.1. It should be noted that the planned projects highlighted in this section were selected as they were deemed to be the most established and most likely to be constructed. There are also a number of other concepts seeking full-scale demonstration before 2020.

Figure 2.9.1. Project capacity and turbine rating for operational and planned multi-megawatt projects up to 2020



N.B. Only includes more advanced projects. Pipeline beyond 2018 is larger, but will be dependent on the success of these early demonstrations, as well as political factors.

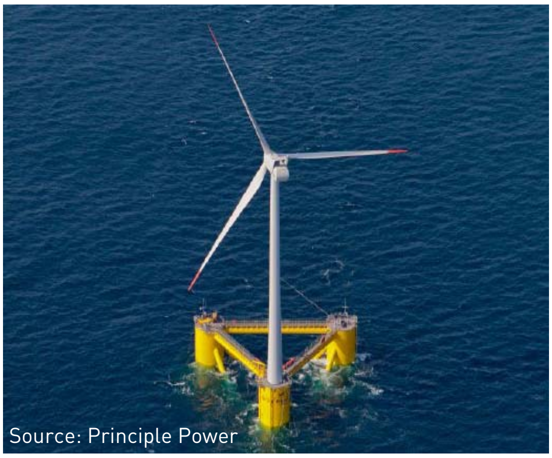
Europe

2009: Hywind Demonstrator (Norway)


Source: Statoil

Leveraging its position as the leading market for fixed-bottom offshore wind, Europe also took the lead in floating offshore wind when the world's first full-scale floating wind turbine was installed off the coast of Norway in 2009. The installation of Statoil's Hywind spar buoy, with a Siemens 2.3 MW turbine, marked a major milestone for floating wind and triggered a great deal of interest in the potential for floating wind to play a key role in a future energy mix beyond 2020. The Hywind device has performed extremely well in the harsh marine conditions of the North Sea and has recorded impressive average load factors of ~50% (~10% more power than conventional fixed-bottom turbines), giving credence to the idea that deep water floating wind can access more abundant wind resources and improve the economics of offshore wind.

2011: WindFloat – Phase 1 (Portugal)


Source: Principle Power

Principle Power's WindFloat semi-submersible became the second full-scale deployment of a floating wind turbine (and the first of a semi-submersible) in 2011, when it was installed 5km off the coast of Aguçadoura, Portugal. The project, developed by EDP Renováveis, was part-funded by the European Commission through the DEMOWFLOAT initiative, and is undergoing ongoing monitoring to extract useful operational data to inform design optimisations. Principle Power are targeting the development of a pre-commercial array in both Europe and the USA by 2018, including an additional 25 MW off the coast of Portugal and a 30 MW array in Oregon, clearing the way for commercial deployment from 2020.

2015: FLOATGEN – IDEOL (France)


Source: IDEOL

Despite limited offshore wind activity to date, France has three floating wind demonstration projects in the pipeline, which could establish the country as a hub for floating wind technology. The first to be installed could be Ideol's concrete semi-submersible concept, which will support a 2 MW Gamesa turbine. The project, which has received funding from the European Commission ('Floatgen') and French Government ('Oceagen'), will be deployed at the SEM-REV testing facility off Le Croisic in le Pays de la Loire, in 2015. Following this initial demonstration, IDEOL have plans to develop a 500 MW wind farm in France with Quadran Energies Libres, as well as additional demonstrations in Japan with Hitachi Zosen.

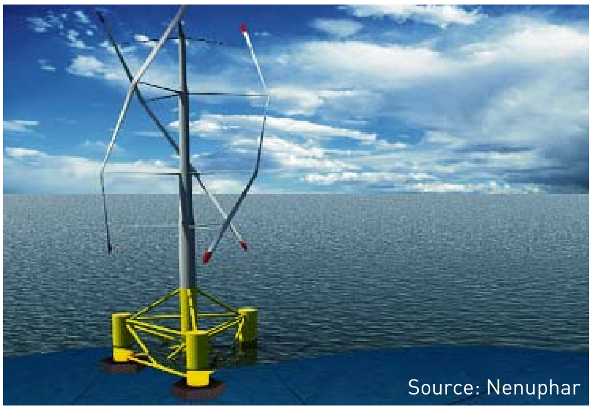

Source: GICON

2015: GICON-SOF Pilot (Germany)

German engineering company GICON are set to install their TLP concept, the GICON-SOF, in late 2015, supporting a 2.3 MW Siemens turbine. If successful, this would be the world's first full-scale TLP floating wind structure. The concept has undergone extensive tank testing since 2012, with the design having been modified to reduce structural mass to maximise its cost reduction potential. GICON have secured a test site and €5.25m funding from the State of Mecklenburg-Vorpommern, with construction of the platform already underway ahead of installation in the German Baltic Sea in the second half of 2015.

2016: VERTIWIND (France)

EDF Energy are planning a 2.6 MW demonstration of Nenuphar's VERTIWIND semi-submersible concept off the south coast of France, which could be in the water as early as 2016. A prototype of the 2.6 MW vertical axis wind turbine has already been constructed and is currently undergoing onshore testing, before offshore deployment in the Mediterranean Sea. Following this initial demonstration, EDF and Nénuphar intend to install a 34 MW pilot farm consisting of thirteen 2.6 MW turbines after 2017.

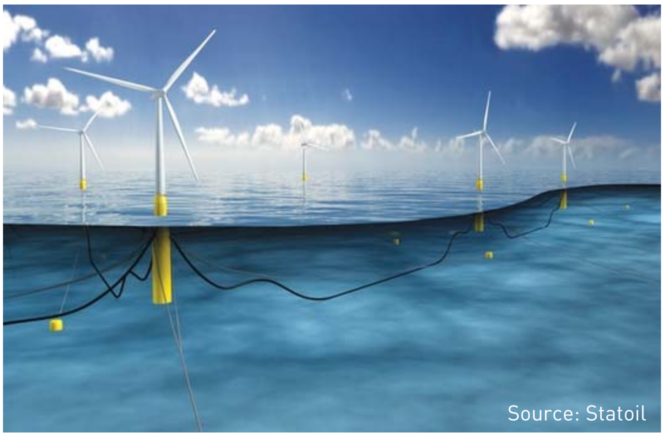

Source: Nenuphar


Source: Principle Power

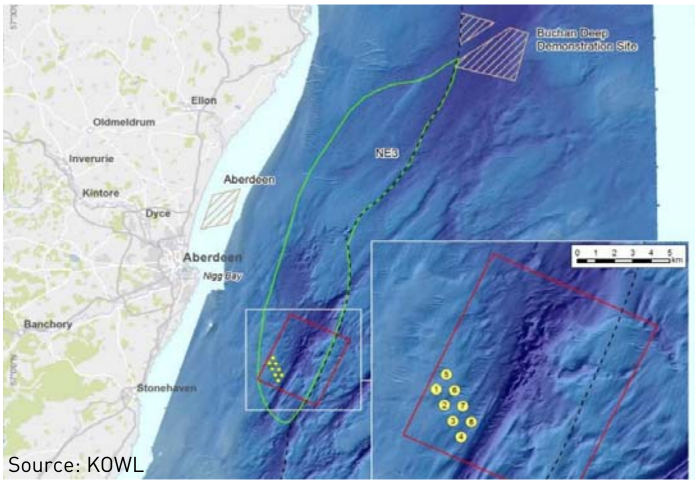
2017: WindFloat – Phase 2 (Portugal)

Building on the success of the 2 MW WindFloat demonstrator installed in 2011, Principle Power have been awarded nearly €50m to build out the second phase of the project off the coast of Aguçadoura. The project, which will reach up to 25 MW installed capacity, has yet to identify a turbine model, but is considering turbines up to 8 MW power rating. The project has been approved by the European Commission to receive a feed-in tariff from the Portuguese Government, in addition to funding grants from FP7 and NER 300, with installation currently earmarked for 2017.

2017: Hywind Pilot Park (Scotland)


Source: Statoil

Building on the success of the 2.3 MW demonstrator, Statoil are planning to deploy the world's first array of floating wind turbines in the Buchan Deep, 25km off the coast of Peterhead on north-east coast of Scotland. The 30 MW array will consist of five 6 MW turbines and will connect to the local grid through an onshore converter station. Statoil, who have been granted a lease to Buchan Deep by the Crowne Estate, are targeting installation during 2017 in order to benefit from the 3.5 Renewable Obligation Certificates (ROCs) offered to floating wind projects in Scotland, and they are currently in negotiations with National Grid for an accelerated connection date to facilitate this. The pilot project is hoping to demonstrate cost reduction of two-thirds versus the 2009 prototype and, if successful, the pilot project could pave the way for commercial developments beyond 2020.



Source: KOWL

2018: Kincardine Offshore Wind Farm (Scotland)

In addition to the Hywind Pilot Park, the attractive 3.5 ROC subsidy support in Scotland is encouraging several floating wind designers to explore opportunities to test their devices in Scottish waters. Two prospective test sites, at Kincardine and Dounreay, respectively, have been identified for pre-commercial arrays. Kincardine Offshore Windfarm Ltd - a joint project between Pilot Offshore Renewables and Atkins - wants to put up to eight 6-8 MW turbines about 10 miles off the east coast of Scotland, south of Aberdeen, for a project of up to 50 MW capacity. The project will provide another opportunity for the Principle Power WindFloat device to be tested in a pre-commercial array, with installation targeted by 2018.

2018: Dounreay Floating Offshore Wind Development Centre (Scotland)

Highlands and Islands Enterprise (HIE) are proposing to construct the Dounreay Floating Offshore Wind Development Centre (DFOWDC) on the north coast of Scotland, which could potentially site five 6 MW floating wind devices by 2018. Concepts have yet to be selected for the test centre, which is racing to secure consent and grid connection in time for demonstration projects to secure the enhanced ROCs on offer up to October 2018.

2018: SEAREED (France)


Source: DCNS-Alstom

Another project backed by strong industrial partners is DCNS' SEA REED project, which is intending to install a 6 MW Alstom turbine on the SeaReed semi-submersible concept. The partnership will combine the expertise of DCNS, as a leading naval architect, with Alstom's Haliade turbine technology. An initial single unit demonstration is slated for 2018 at the Groix test site off the coast of Brittany, with commercial deployment expected beyond 2020 following a pre-commercial pilot project.

Japan

Although Europe may have installed the first floating wind turbines, Japan is rapidly taking the lead in floating wind technology. Largely triggered by the Fukushima nuclear disaster in 2011, the Japanese Government have invested considerably in floating wind projects in order to tap into the huge potential for floating wind in Japan.


Source: MOE

2013: Kabashima

Following an initial 100 kW prototype, a full-scale 2 MW unit of Toda Corporation's hybrid concrete-steel spar buoy was installed off the coast of Kabashima in the Goto Islands in 2013. The project, funded by the Japanese Ministry of the Environment (MOE), was the first grid-connected floating wind turbine in Japan and has also been used to monitor the environmental impact of offshore wind structures. Since being installed, the spar and 2 MW Fuji turbine have performed very well, surviving a typhoon in September 2012 unscathed. The MOE have since announced that it will fund a detailed environmental impact assessment study for a 522 MW project in the Goto Islands, which will include both 2 MW and 5 MW units of the spar buoy structure.

2013-2015: Fukushima FORWARD – Phase 1 and Phase 2


Source: Fukushima FORWARD

Following the Fukushima nuclear disaster in 2011, the Japanese Government stated its intent to build the world's largest floating offshore wind farm in the Fukushima prefecture, with a long-term goal to install up to 1 GW of capacity, following a phased RD&D approach. The first phase of the Fukushima FORWARD (Floating Offshore Wind Demonstration) project, which is being developed by a consortium headed by Marubeni Corporation, consisted of installing one 2 MW turbine on a four-column semi-submersible foundation together with the world's first floating substation, on an advanced spar concept; both of which were successfully installed in 2013. The next phase of the project will


Source: Mitsubishi Heavy Industries

see a Mitsubishi Heavy Industries 7 MW SeaAngel turbine installed on a V-shape semi-submersible platform in 2015, followed by a 5 MW Hitachi turbine on another advanced spar, expected in 2016. The iconic project has become a hub for floating wind RD&D and places Japan at the forefront of floating wind technology. The Japanese Government hope to expand the wind farm to 100 MW in time for the 2020 Tokyo Olympics, with a long-term goal of reaching up to 1 GW, but demonstrating cost reduction will be critical to achieve this.

USA

2017: WindFloat Pacific

The United States is another potentially large market for floating wind. The US installed its first offshore wind turbine in 2013 in the form of a part-scale prototype of the VolturnUS semi-submersible concept, and the US Department of Energy (DOE) has since funded initial design studies for three full-scale floating wind projects, including a 6 MW VolturnUS demonstration, a pilot project for Statoil's Hywind concept in the Gulf of Maine, and a pre-commercial array for Principle Power's WindFloat device off the Pacific west coast. In 2014 the latter was selected to receive a further $47 million to build the 30 MW project, which will consist of five 6 MW floating turbines. Installation is expected in 2017.

2018: Maine Aqua Ventus I

Despite missing out on the initial funding, the University of Maine's demonstration of two VolturnUS 6 MW units remains an alternative for the DOE, and is still targeting an installation date in the summer of 2018. A lease has been granted and site surveys have been completed, with a 20 year power purchase agreement in place for a 20 year period, offering $23.5 cents/kWh. Beyond this first full-scale demonstration there are plans for an additional 480 MW in the second phase and possible up to 5 GW of floating wind installed in Maine in the long term.

Source: University of Maine

WindFloat Hawaii

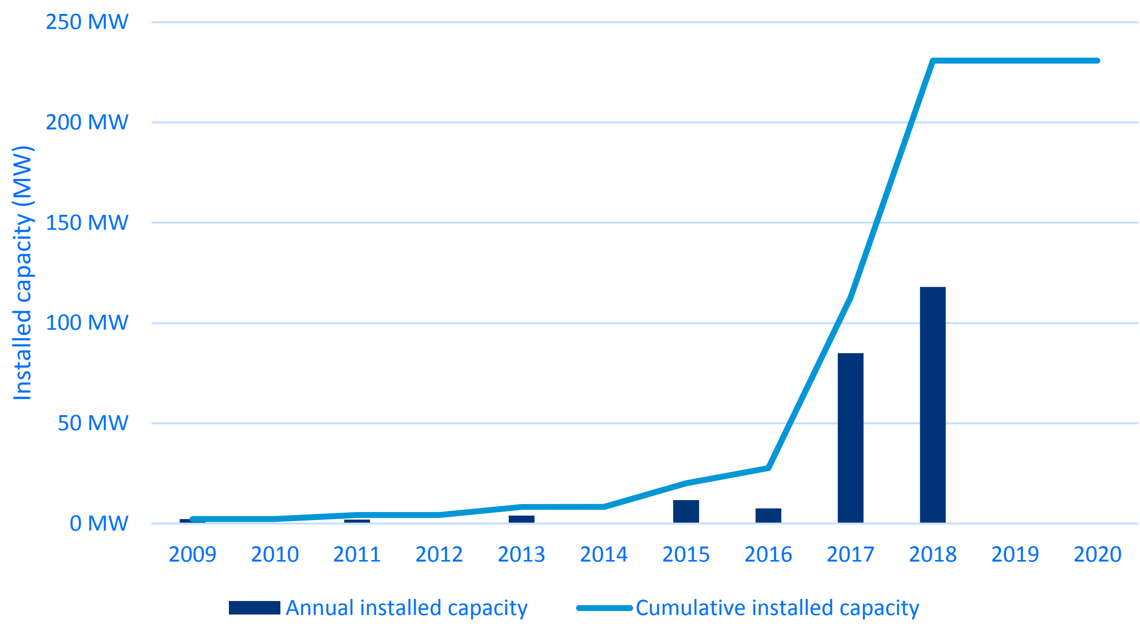
Meanwhile, Principle Power are also targeting two large commercial project in Hawaii, having submitted an unsolicited application to the US Bureau for Ocean Energy Management (BOEM) for two leases for project which could reach up to 408 MW each, consisting of 51 8MW turbines supported by the WindFloat structure.

Build-out of floating wind

Despite just 8 MW of floating wind installed to date, build out is expected to increase sharply over the next few years, as the projects listed above come online (figure 2.9.2). With a handful of demonstrations expected in 2015 and 2016, installed capacity is expected to spike in 2017 and 2018 as a number of pre-commercial arrays are constructed. While the phasing may alter, with some projects experiencing delays or falling away and new developments coming online, we expect that the cumulative capacity of ~240 MW is certainly attainable by 2020, and the success of these projects will likely determine build out rates in the subsequent decade. Projects in the UK could constitute almost half of global installed capacity 2020, with 108 MW in the pipeline, all of which is located in Scotland.

The spike in 2018 is largely stimulated by the end of the availability of Renewable Obligation Certificates (ROCs) for floating wind in Scotland, which has triggered a race to get projects in the water ahead of the October 2018 deadline. Three pre-commercial arrays totalling over 100 MW are targeting deployment in Scotland. Failing to secure a contract could put projects at risk, leaving progress contingent on a follow-on subsidy support mechanism for floating wind. Project failures could divert investment away from Scotland to other markets, where more favourable support can be sought. Conversely, securing a contract will give designers the opportunity to prove their technologies and, if cost competitiveness can be demonstrated, this could open the opportunity for commercial deployment from 2020, bringing significant investment to Scotland.

Figure 2.9.2. Build out of floating wind based on current projects under development



N.B. Only includes more advanced projects. Pipeline beyond 2018 is larger, but will be dependent on the success of these early demonstrations, as well as political factors.

Table 2.9.1. Operational and planned floating wind projects

Status	Commissioning (actual/planned)	Country	Project	Project capacity	Concept	Typology	Manufacturer	Developer	Turbine capacity	Turbine manufacturer
Operational	2009	Norway	Hywind demonstrator	2.3 MW	Hywind	Spar	Statoil	Statoil	2.3 MW	Siemens
Operational	2011	Portugal	WindFloat - Phase 1	2 MW	WindFloat	Semi-sub	Principle Power	EDPR/Repsol	2 MW	Vestas
Operational	2011	Norway	Sway	0.015 MW	Sway	Spar	Sway A/S	Sway A/S	0.015 MW	Sway A/S
Operational	2012	Japan	WindLens Project - Phase 1	0.008 MW	WindLens	Multi-turbine platform	RIAMWIND/ Kyushu University	RIAMWIND/ Kyushu University	0.003 MW	RIAMWIND
Operational	2013	USA	VolturnUS 1:8 Prototype	0.02 MW	VolturnUS	Semi-sub	DeepCWind Consortium	DeepCWind Consortium	0.02 MW	Renewegy
Operational	2013	Japan	Kabashima (Goto Islands)	2 MW	Hybrid concrete-steel spar	Spar	Toda Corporation	Toda Corporation; Fuji Heavy Industries; Fuyo Ocean Dev. & Eng.	2 MW	Hitachi
Operational	2013	Japan	Fukushima FORWARD - Phase 1	2 MW	Compact semi-sub	Semi-sub	Mitsui	Marubeni Corporation	2 MW	Hitachi
					Advanced spar	Spar	Japan Marine United		NA - Substation	Hitachi
Under Construction	2015-2016	Japan	Fukushima FORWARD - Phase 2	12 MW	V-shape semi-sub	Semi-sub	MHI	Marubeni Corporation	7 MW	MHI
					Advanced spar	Spar	Japan Marine United		5 MW	Hitachi

Status	Commissioning (actual/planned)	Country	Project	Project capacity	Concept	Typology	Manufacturer	Developer	Turbine capacity	Turbine manufacturer
Under Construction	2015	Germany	GICON-SOF Pilot	2.3 MW	GICON-SOF	TLP	GICON	GICON	2.3 MW	Siemens
Consented	2015	France	FLOATGEN	2 MW	Ideol	Semi-sub	Ideol	FLOATGEN	2 MW	Gamesa
Consented	2015	Japan	MODEC SKWID Demonstration	0.5 MW	SKWID	Hybrid wind/wave	MODEC	MODEC	0.5 MW	MODEC
Consented	2016	France	Vertiwind - Mistral	2.6 MW	Vertiwind	Semi-sub	Nenuphar	EDF Energy	2.6 MW	Nenuphar
Planned	2017	Portugal	WindFloat – Phase 2	25 MW	WindFloat	Semi-sub	Principle Power	EDPR/Repsol	8 MW	TBC
Planned	2017	UK (Scotland)	Hywind Pilot Park	30 MW	Hywind	Spar	Statoil	Statoil	6 MW	TBC
Planned	2017	USA	WindFloat Pacific	30 MW	WindFloat	Semi-sub	Principle Power	Deepwater Wind	6 MW	TBC
Planned	2018	UK (Scotland)	Kincardine	48 MW	WindFloat	Semi-sub	Principle Power	Atkins; Pilot Offshore	6 MW	TBC
Planned	2018	UK (Scotland)	Dounreay	30 MW	TBC	TBC	TBC	TBC	TBC	TBC
Planned	2018	France	SEA REED (Groix)	6 MW	SEA REED	Semi-sub	DCNS	DCNS-Alstom	6 MW	Alstom
Planned	2018	France	Provence Grand Large	34 MW	Vertiwind	Semi-sub	Nenuphar	EDF Energy	2.6 MW	Nenuphar
Planned	2018	USA	Maine Aqua Ventus I	12 MW	VolturnUS	Semi-sub	University of Maine	University of Maine	6 MW	TBC

2.9.2 Research, Development and Demonstration Initiatives

Research, development and demonstration (RD&D) activity in floating wind has increased significantly over the past 5-6 years, with a handful of concepts having already progressed from concept development and tank testing to full-scale demonstrations with multi-megawatt turbines, and a number of others expecting to deploy full-scale prototypes or pre-commercial arrays by 2018 (table 2.9.2). Public research grants have generally been successful in supporting early concept development and tank testing, as well as a handful of full-scale demonstrations; although progressing to the latter has been a challenge for some, largely due to the significant step up in costs.

Most RD&D initiatives are undertaken by consortia, often vertically integrated, consisting of companies across the supply chain with varied and unique capabilities to support the delivery of the project. Research has also almost exclusively focussed on individual concepts, rather than tackling common industry-wide challenges. As more concepts are deployed there may be scope to develop RD&D activities to tackle common challenges, sharing knowledge between the various individual initiatives to improve learning rates and overcome key challenges for the industry. An early example of this form of activity is a joint industry project being led by DNV-GL which will create industry guidelines on coupled dynamic analysis of floating wind turbines, set to kick off in 2015.

In Europe, most floating wind activity has been enabled by European Commission funding calls – namely the Seventh Framework Programme (FP7) and NER300 – with significant grants also provided by some national governments – particularly ADEME (the French Agency for Environment and Energy Management), the Norwegian Research Council, and the Energy Technologies Institute in the UK. In Japan, RD&D has largely been supported by the Ministry of Economy, Trade & Industry (METI), who have invested JPY 53 bn (£29m) in the Fukushima FORWARD project, which has become the central hub for floating wind RD&D in Japan. The Ministry of the Environment has also funded a full-scale demonstration project – a spar buoy concept at Kabashima. Meanwhile, in the United States, the Department of Energy is the sole funder of RD&D activities, which has included a series of $4 million grants to support FEED studies for three floating concepts, and a $47 million (£30.6m) grant to develop a pre-commercial array of Principle Power's WindFloat device off the coast of Oregon.

However, the pace of development has been slower than anticipated for a number of concepts, often owing to the lack of an industrial partner to leverage public funding and lend their expertise to progress the design to the demonstration phase (See section 4 for more detail on concept technology readiness). It is therefore unsurprising that those concepts which have been successfully deployed with multi-megawatt turbines have done so with the support of established industry partners.

Table 2.9.2. Research, development, and demonstration initiatives

Region	Country	Time period	Initiative	Activity	Concept(s) supported	Typology	Unit capacity	Funding	Funding (£)	Funding source(s)	Status
EUROPE	Spain	2007-2010	EOLIA	Tank testing	Acciona	Semi-sub	Tank test	€ 33.9 m	£ 25.0 m	Centre for the Development of Industrial Technology (CDTI) (€16.7m)	Closed
	Norway	2009	Hywind Demonstration	Full-scale prototype	Hywind	Spar	2.3 MW	€ 6.9 m	£ 5.0 m	Enova (€6.9)	Closed
	Europe (Spain/ Norway)	2010-2015	HiPR Wind	Full-scale prototype	HiPRWIND	Semi-sub	1.5 MW	€ 19.8 m	£ 14.6 m	EC FP7 (European Commission Seventh Framework Programme) (€11.0m)	On hold
	Norway	2011	Sway	Full-scale prototype	Sway	Spar	0.015 MW			Norwegian Research Council	Closed
	Europe (Portugal)	2011-2014	DEMOWFLOAT	Full-scale prototype	WindFloat	Semi-sub	2.0 MW	€ 6.0 m	£ 4.4 m	EC FP7 (€3.6m)	Closed
	Europe	2011-2015	MARINET (Marine Renewables Infrastructure Network)	Tank testing	Various	Various	Various	€ 11.1 m	£ 8.2 m	EU FP7 (€9.0m)	Active
	Europe (France)	2011-2015	InFLOW (INdustrialization setup of a FLoating Offshore Wind turbine)	Full-scale prototype	VERTIWIND	Semi-sub	2.0 MW	€ 21.5 m	£ 15.8 m	EC FP7 (€11.9m)	Active
	UK	2012-2015	DECC Offshore Wind Component Technology Scheme	Tank testing	TetraFloat	Semi-sub	Tank test	£ 0.2 m	£ 0.2 m	UK Department for Energy and Climate Change (DECC) (£0.2m)	Active

Region	Country	Time period	Initiative	Activity	Concept(s) supported	Typology	Unit capacity	Funding	Funding (£)	Funding source(s)	Status
EUROPE	Germany	2012-2015	GICON Schwimmendes Offshore Fundament (SOF) Pilot	Full-scale prototype	GICON SOF	TLP	2.0 MW	€ 18.0 m	£ 13.2 m	German Ministry of Economy, Construction, and Tourism (€5.25m)	Active
	Europe (Portugal)	2013-TBC	WindFloat	Pre-commercial array	WindFloat	Semi-sub	8 MW (27 MW array)	€ 48.9 m	£ 36.0 m	Portuguese Government (€19m); NER300 (€29.9m)	Active
	Norway	2013-2016	FLEXWT (Floating Experimental Wind Turbine)	Part-scale prototype	TBC	TBC	0.2-0.4 MW	€ 5.0 m	£ 3.7 m	Norwegian Research Council (€5m)	Active
	UK	2013-2017	WaveHub Floating Wind Demonstration	Full-scale prototype	PelaStar	TLP	6.0 MW	£ 25.0 m	£ 25.0 m	Energy Technologies Institute (£25m)	Cancelled
	France	2014-2016	VALEF2	Design methodologies	Various	Various	N/A	€ 2.1 m	£ 1.5 m	France Energies Marines	Active
	Europe (France)	2014-2018	FLOATGEN	Full-scale prototype x2	1: IDEOL; 2: Navantia TBC	Semi-sub	2.0 MW	€ 36.3 m	£ 26.7 m	EC FP7 (€19.6m)	Demo 1 Active; Demo 2 Cancelled
	France	2015-2018	OCEAGEN	Full-scale prototype	IDEOL	Semi-sub	2.0 MW	€ 12.3 m	£ 9.1 m	ADEME (French Agency for Environment and Energy Mgmt) (€7.3m); Private investors (€3.8m); BNP Paribas/Caisse d'Epargne (€1.2m - loan)	Active
	France	2015-2018	SEA REED	Initial testing & certification	SeaReed	Semi-sub	6.0 MW	€ 6.0 m	£ 4.4 m	ADEME (€6m)	Active

Region	Country	Time period	Initiative	Activity	Concept(s) supported	Typology	Unit capacity	Funding	Funding (£)	Funding source(s)	Status
ASIA	Japan	2006-TBC	WindLens	Full-scale prototype	WindLens	Multi-turbine platform	0.008 MW			Kyushu University	Active
	Japan	2011-2013	GOTO FOWT	Full-scale prototype	Hybrid concrete-steel spar	Spar	2.0 MW	JPY 6 bn	£ 32.8 m	Japanese Ministry of the Environment (MOE) (JPY 6bn)	Active
	Japan	2011-2015	Fukushima FORWARD	Full-scale prototype x4	Advanced spar x2; Compact semi-sub; V-shape semi-sub	Spar; Semi-sub	2 MW, 7 MW, & 5 MW (14 MW array)	JPY 53 bn	£ 289.5 m	Japanese Ministry of Economy, Trade, and Industry (METI) (JPY 53bn)	Active
	Japan	2012-TBC	MODEC SKWID	Full-scale prototype	SKWID	Hybrid wind/wave	0.5 MW			New Energy and Industrial Technology Development Organization (NEDO)	Active
NORTH AMERICA	USA	2008-2014	DeepCwind Consortium - VolturnUS	Full-scale prototype	VolturnUS	Semi-sub	0.02 MW	$ 12.0 m	£ 7.8 m	US Department of Energy	Closed
	USA	2012-2014	Maine Aqua Ventus I	FEED Study	VolturnUS	Semi-sub	6.0 MW	$ 4.0 m	£ 2.6 m	US Department of Energy	Closed
	USA	2012-2014	Statoil Gulf of Maine	FEED Study	Hywind	Spar	6.0 MW	$ 4.0 m	£ 2.6 m	US Department of Energy	Closed
	USA	2012-2014	WindFloat Oregon	FEED Study	WindFloat	Semi-sub	6 MW (30 MW array)	$ 4.0 m	£ 2.6 m	US Department of Energy	Active
	USA	2014-2018	WindFloat Oregon	Pre-commercial array	WindFloat	Semi-sub	6 MW (30 MW array)	$ 47.0 m	£ 30.6 m	US Department of Energy	Active

2.10 Test Sites and Facilities

2.10.1 Tank testing

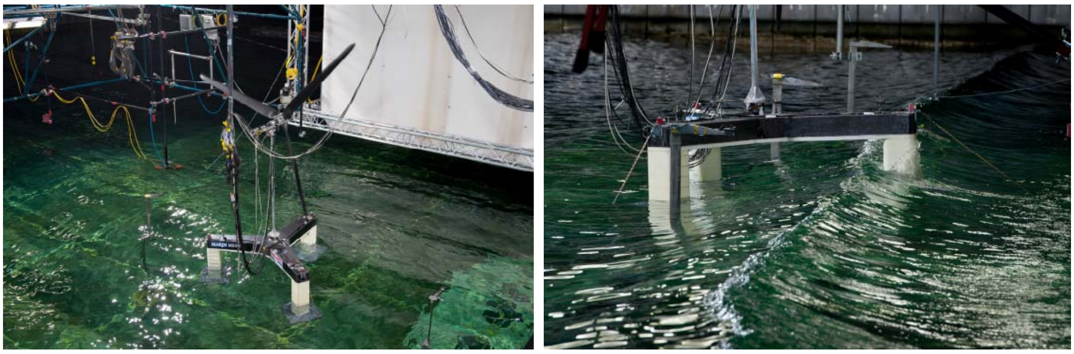
Once a concept has been designed and simulated, it must undergo testing to validate its performance in real dynamic conditions, initially through small scale tank testing (typically ~1:30 to 1:60 scale) before progressing to part- and full-scale offshore demonstrations. The MARINET (Marine Renewables Infrastructure Network) programme, funded under the European Commission's Seventh Framework (FP7), has successfully provided opportunities for innovators to conduct tank testing for their floating wind concepts in Europe, but with the programme set to close in 2015, opportunities to tank test designs could become scarcer.

There are several tank testing facilities in Europe which are able to simulate offshore conditions; two of which are located in the UK (table 2.10.1; note that small facilities designed for vessel tests have not been included in the list). Most of these facilities were originally established for testing ships and floating platforms for the oil and gas industry, but in recent years they have been adapted to undertake testing of offshore wind structures. While wave and currents are the dominant factors for floating structures in the oil and gas industry, for floating wind turbines wind is an increasingly significant factor, which requires higher quality wind simulations in the test basin. At MARIN (Maritime Research Institute Netherlands) multiple large fans have been used in combination with a barrier with holes to streamline the airflow and create turbulence representative of the wind conditions experienced offshore.

Table 2.10.1. Tank testing facilities in Europe

Test facility	Country
BGO First, OCEANIDE	France
ECN - Hydrodynamic and Ocean Engineering Tank, Nantes	France
Ifremer, Brest	France
Hamburg Ship Model Basin	Germany
UCC-BEAUFORT; formerly, HMRC (Hydraulics and Maritime Research Centre), University College Cork	Ireland
CNR-INSEAN	Italy
MARIN (Maritime Research Institute Netherlands)	Netherlands
MarinTek	Norway
Environmental Hydraulics Institute IH Cantabria	Spain
COaST (Coastal Ocean and Sediment Transport Laboratories), Plymouth University	UK (England)
FloWave Ocean Energy Research Facility	UK (Scotland)

Figure 2.10.1. Scale model testing of the GustoMSC Tri-Floater at the MARIN test facility, Netherlands (GustoMSC, 2013)

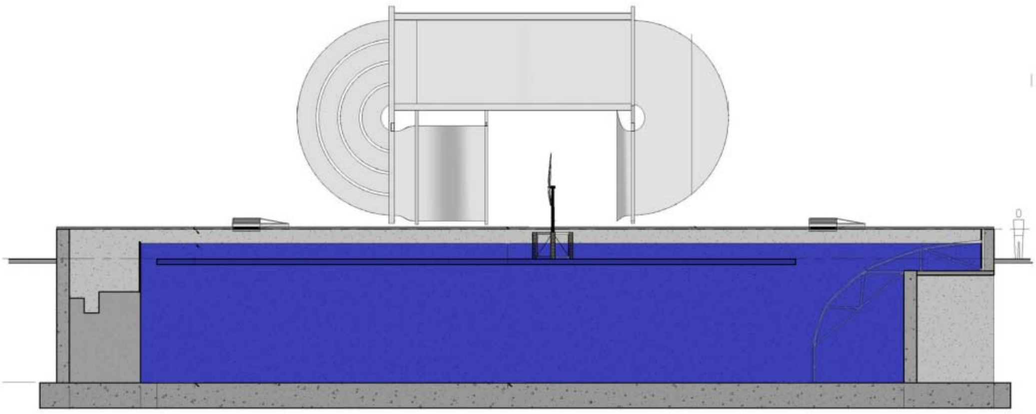


Given the growing level of interest in floating wind technology, there is scope to develop more advanced tank testing facilities to test floating wind structures, which replicate wave and wind conditions in a more realistic manner. Scotland is fortunate to already have one such facility in the FloWave Ocean Energy Research Facility, located at Edinburgh University, which is considered one of the most sophisticated ocean simulators in the world. Though originally designed for wave and tidal devices, the centre is now extending its remit to floating wind devices. FloWave consists of a 25m diameter circular tank designed specifically to replicate wave and current conditions for North Sea offshore environments. 168 absorbing wave makers surrounding the tank are able to simultaneously produce complex multi-directional waves and fast currents, with an elevating floor that can test devices in different water depths. FloWave are able to retrofit the tank to simulate wind conditions, and are currently exploring the most effective means of doing so to support accurate validation with numerical models.

Figure 2.10.2. FloWave Ocean Energy Research Facility (FloWave, 2015)

Another advanced tank testing facility is under construction in the United States. The 'W^2 Wind-Wave Basin' at the University of Maine is currently under construction and will be equipped with an integrated rotating open-jet wind tunnel over a wave basin, which will enable it to combine full wave and wind loads from multiple directions, such that waves can be propagated at a different angle to the wind. The 30m x 9m basin is also equipped with a variable depth floor to simulate conditions at different water depths, and the wave maker at one end of the basin will be capable of creating waves of varying frequency and direction, as high as 0.6m. Wind velocities will be able to reach up to 7 m/s. The $100m basin has been funded by a range of public grants and is expected to be completed in 2015. It can also be used to test naval vessels, oil and gas structures, as well as the effects of coastal erosion and sea level rise.

Figure 2.10.3. Schematic of the W^2 Wind-Wave Basin at the University of Maine (University of Maine, 2014)



Advanced tank testing facilities such as those as FloWave and the University of Maine can help to de-risk and optimise the design as much as possible before moving to full-scale offshore demonstrations, which can ultimately lead to less conservative and more competitive designs, helping to bridge the 'valley of death' between model and full-scale testing. The facilities can also serve as centres of excellence for floating wind technology and build strong links with academic institutions. This could be one way for Scotland to position itself at the forefront of floating wind technology in Europe, and potentially at a global level.

2.10.2 Offshore demonstration sites

Demonstrating the performance and reliability of foundation concepts is often the final step in proving the technology and making it available for use in commercial projects. However, there are concerns across the industry that plans to commercialise new foundations are at risk because of a lack of demonstration sites available for testing new devices, which is largely attributed to strict consenting procedures and the excessive costs of providing electrical infrastructure to connect a small number of turbines to the grid, particularly given the limited commercial opportunities to recoup the expenditure. For fixed foundations it is expected that demonstration opportunities will likely arise from opportunities within or alongside existing commercial wind farms, significantly reducing the consenting time required and leveraging the existing electrical infrastructure. However, the absence of any commercial floating projects means that this isn't possible for floating concepts. Demonstrations must therefore be located at individual sites, requiring significant funding support from the public sector.

It is unsurprising that available test sites are situated in countries with favourable policy support for floating wind (table 2.10.2). After a handful of demonstrations in Norway and Portugal, two potential test sites in Spain were shelved due to the absence of commercial follow-on projects in the region, emanating from a lack of support for renewables in Spain. However, a number of opportunities to test floating devices are beginning to emerge, particularly in France, Portugal, and the UK – particularly in Scotland – where favourable policies have encouraged activity.

Table 2.10.2. Offshore test sites for floating wind technologies in Europe

Test site	Country	Concepts tested/ to be tested	Installation date
Karmoy, Rogaland	Norway	Hywind I	2009
Hordaland	Norway	Sway	2011
Aguçadoura	Portugal	WindFloat	2011
German Baltic Sea	Germany	GICON-SOF	2015
SEM-REV, Le Croisic, Pays de la Loire	France	IDEOL	2015
MISTRAL, Fos-sur-Mer, Marseille	France	VERTIWIND	2016
Buchan Deep, Peterhead	UK (Scotland)	Hywind II	2017
Dounreay Floating Offshore Wind Development Centre (DFOWDC)	UK (Scotland)	TBC	2018
Kincardine	UK (Scotland)	WindFloat	2018
Le Groix, Brittany	France	SeaReed	2018
Côte d'Albâtre (proposed 105 MW demonstration site)	France	TBC (Various)	TBC
Utsira (developed by Lyse)	Norway	Sway	TBC
WaveHub, Cornwall	UK (England)	PelaStar	Cancelled
BIMEP, Bay of Biscay	Spain	HiPRWIND	Cancelled
Zefir Test Station	Spain	-	Cancelled

Optimal site conditions for floating wind

Offshore wind needs radical cost reduction to compete with the lowest cost forms of low carbon generation in any future UK energy mix. To achieve this wind farms need to be built on the best sites, which are cheaper to develop and can provide maximum yield. Optimal sites for floating wind projects must therefore adhere to the following requirements:

- Water depth: Most floating wind concepts require a minimum water depth of ~40m, with others requiring deeper waters, particularly spar-buoys. The optimal depth is considered to be from ~100m, since above this depth the moorings are able to take more of the load and displace some of the force placed on the anchors, resulting in a more balanced and cost effective mooring and anchoring system. From ~150-200m, the cost will then begin to increase again as the total mass of the moorings increases.
  Another important consideration for spar-buoys is that they require access to a sheltered deep water location for erection of the structure and turbine assembly. There will also need to be a navigational route with sufficiently deep water to transport the full structure in an upright position.
- Wind speed: As a major driver of yield and power output, the average wind speeds and wind regime at a given site is a major factor in the levelised cost of energy that can be derived. Although high wind speed increases the loads on the structure, which can increase the size of structures and therefore the capital expenditure, the increases in CAPEX is expected to be negated by the increased power output and yield derived, which will result in a net reduction to the levelised cost of energy across the wind farm. For example, modelling of the PelaStar concept calculated a variance in steel weight of 6.1% over a range of wind speeds, while annual energy production varied by 13% over the same range of wind speeds (Glosten Associates, 2014).
- Met-ocean conditions: The design of the floating structure will be predicated by the met-ocean conditions at the site, particularly the extreme wave height expected. The greater the extreme wave height, the more conservative the design, with associated increased in weight and cost. A site with low extreme wave height is therefore desired, though this does not always correlate with sites with the desired high wind speeds.
  Calmer met-ocean conditions are also desirable to increase the weather window available for installation and to conduct maintenance.
- Geotechnical conditions: Geotechnical conditions are an important factor in determining the anchoring system that can be used. Favourable conditions to allow flexibility over the choice of anchor type and to maximise holding capacity are typically cohesive soils that are not too stiff to prevent penetration into the seabed, but also not too loose to limit the resistance of the soils. However, the optimal conditions will depend on the anchoring system used.
- Proximity to grid connection point: An obvious requirement is to be able to connect to the onshore grid, preferably without expensive grid upgrades. The proximity of the offshore site to the onshore grid connection point will also impact on costs. Closer to shore means shorter export cables and reduced transmission losses. Restricting the transmission distance to less than 70-100km will also avoid having to use expensive HVDC technology, which has proved to be highly troublesome to date.
- Proximity to port: Proximity to port is also an important consideration. Transit time during installation will impact on project CAPEX, particularly given how it will influence the available weather windows. The ability to reach offshore site quickly will also reduce OPEX by reducing turbine downtime and enabling maintenance to be conducted from an onshore base.

- Port facilities: The quality of port facilities is also likely to impact project CAPEX, particularly for fabrication, assembly, and installation. Advanced manufacturing equipment can maximise the speed at which structures can be fabricated and, in combination with a large yard size for set-down, this will reduce the time from factory to site to support the rapid roll-out of structures at a commercial wind farm.
  Dry dock facilities are also usually preferable for floating wind devices, since they allow the structure be assembled and launched by flooding the dock, rather than using expensive heavy lift cranes. However, many dry dock facilities were designed for the manufacture and repair of vessels (long and slender structures), which means that there is a limited offering of dry docks for wide structures with large beam. This could generate bottlenecks for commercial developments adopting serial production manufacturing.
  Water depth at the assembly berth is also important, particularly for concepts which require installation barges (i.e. TLPs). Greater depth at the assembly berth does not limit installation barge draft, which provides greater selection of the barges that could be used for assembly and installation, thereby de-risking barge availability.
- Proximity of suppliers: Being close to suppliers will also help to reduce project costs, particularly with regard to the logistics of transporting components to port for assembly (e.g. turbine, steel materials, moorings, anchors, electrical cabling).

UK

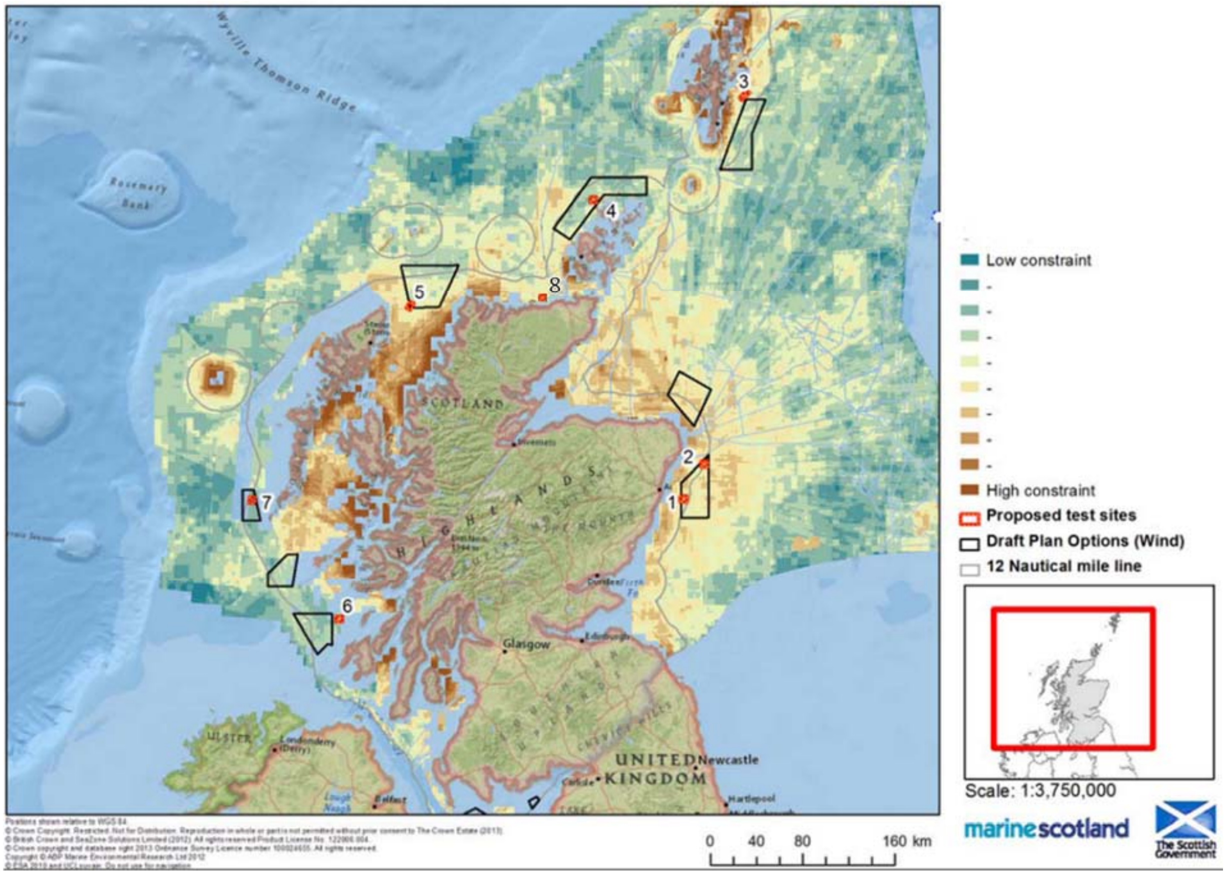
Despite being the world leader in installed capacity of fixed offshore turbines, the UK currently has no floating wind turbines installed. However, a number of demonstrations are in the pipeline, all of which are based in Scotland. The only initiative previously active outside of Scotland was the ETI-funded Floating Offshore System Demonstrator at the Wave Hub test facility in Cornwall, though this was recently cancelled as a result of consenting delays.

Many of the existing leases around the coast of the UK are not suitable for floating technology due to the shallow water depths of these sites. Round 3 sites were selected on the basis of identifying areas of high wind resource where fixed-bottom foundations could be installed at lowest cost, hence shallow water depths. Although the deeper Round 3 and Scottish Territorial Water sites in the 50-60m depth range could host floating wind turbines, they are not in line with the optimal conditions which would yield a lower cost of energy – thought to be in the 80-100m depth range.

In response to the lack of opportunities to demonstrate floating wind concepts in the UK, in 2013 the Crown Estate opened a leasing round for new floating wind demonstration sites of up to 100 MW installed capacity. Developers were asked to propose areas of the seabed that could be suitable for pilot projects, with a view to construction getting under way at selected demonstration sites from 2017. The leasing round closed in April 2015 without awarding any rights for development in the UK.

However, it has triggered the identification of a handful of sites in Scotland which could be used to demonstrate floating wind technology. A study by Marine Scotland (2014) used the Crown Estate's MaRS tool to identify a number of potential development zones for floating wind projects, for both demonstration and commercial developments (figure 2.10.4). The tool was used to assess wind resource (minimum annual wind speed of 9 m/s), water depth (>35 m), grid connection, port facilities, and various constraints such as shipping routes, fishing activity, conservation zones, military activity etc. Two of the seven sites identified are being pursued for pre-commercial floating wind projects, and another has since been identified in Dounreay (site no.8 in figure 2.10.3). Further details on these three sites are included below. For additional information on the site conditions of all of the seven locations identified, see Marine Scotland (2014) 'Potential Scottish Test Sites for Deep Water Floating Wind Technologies'.

Figure 2.10.4. Locations identified for floating wind development in Scotland (Marine Scotland, 2014)



N.B. The report notes that a number of other development zones, particularly off the east coast of Scotland, could also be exploited if more locations are required or certain constraints are relaxed. Sites: 1) South-East of Aberdeen (Dog's Hole, Kincardine); 2) North-East of Aberdeen (Buchan Deep, Peterhead); 3) East of Shetland; 4) East-West of Orkney; 5) North of Minch; 6) West of Colonsay; 7) West of Barra. Site 8 has been added by Carbon Trust to indicate the location of the proposed Dounreay Floating Offshore Wind Deployment Centre.

Buchan Deep, Peterhead (Scotland):

Statoil have identified the Buchan Deep, off the coast of Peterhead, Scotland, to install a 30 MW pre-commercial array of the Hywind spar-buoy. The site is relatively close to shore (20-25km), enabling quick access to the array, and met-ocean conditions and water depths well-suited to the Hywind concept. The site is 95-120m deep and has access to a sheltered deep water area for offshore turbine assembly. Peterhead has a suitable onshore grid connection point which the array will be able to connect to directly, removing the need for an offshore substation. An added benefit is that there is well established infrastructure and supply chain in the area from the offshore oil industry, which can be leveraged to support floating wind projects.

Dog Hole, Kincardine (Scotland):

Kincardine Offshore Wind Farm Limited (KOWL), a joint venture between Pilot Offshore Renewables and Atkins, want to deploy eight wind turbine generators, with individual capacity no less than 6MW, on semi-submersible floating platforms near the Dog Hole off Aberdeen. Principle Power's WindFloat has been identified as a likely candidate to supply the foundations. The site is located 15km from shore in water depths of 60-80m, hence the preference for a semi-submersible concept. Like Buchan Deep, the project does not feature an offshore substation, as the wind turbines would be connected directly to the grid at Redmoss onshore substation via two transmission lines.

Dounreay (Scotland):

Dounreay Floating Offshore Wind Deployment Centre (DFOWDC) is a proposed test site off the north coast of Scotland being develop by Highlands and Islands Enterprise (HIE). It is an innovative 30 MW test and demonstration facility located approximately 6nm north-west of the Dounreay nuclear installation, which will allow the facility to tap into the existing electrical infrastructure in the area. The site will have the capacity to deploy up to 5 floating turbines in water depths of between 77-110m, with an average depth of 85m across the site. HIE are actively working to ready the site before the 2018 ROC deadline, with securing grid connection identified as the most significant potential stumbling block.

WaveHub, Cornwall (England):

The WaveHub test centre off the north coast of Cornwall is a bespoke test facility for offshore renewable technologies. The WaveHub consists of an electrical hub on the seabed which acts as a shared connection point for ocean energy devices. There are four berths, of which three are to be used for wave devices and one was reserved for a floating wind device. The purpose built hub was installed in 2010 with grid connection for up to 30 MW capacity. The site is located just 16km from shore in water depths of 48-58m, in close proximity to a variety of ports and expert academic institutions specialising in offshore renewables. A planned demonstration of the PelaStar TLP concept was recently cancelled, but there remains a possibility to demonstrate other devices at the site.

France

In France, two concepts have benefitted from funding from ADEME (French Environment and Energy Management Agency) to secure demonstration sites off the north-west coast. The SEM-REV test centre at Le Croisic, in the Pays de la Loire, will host the IDEOL semi-sub as part of the FLOATGEN/OCEAGEN project, with installation slated for 2015. The research test site is already equipped with a high voltage subsea cable and onshore substation, as well as a ground research centre owned by Ecole Centrale de Nantes for monitoring and analysis. SEM-REV, however, is deemed too shallow for DCNS and Alstom's semi-sub, part of the SeaReed project, which is now expected to be demonstrated at Le Groix, off the coast of Brittany, in 2017. Le Groix will be split into two sections; the first for demonstrating individual machines and the second for a pilot wind farm of 4-6 turbines (Wind Power Offshore, 2013).

In the Mediterranean, the MISTRAL test site off Fos-sur-Mer, Marseille, will host the world's first vertical axis floating wind turbine, VERTIWIND, as part of the InFLOW project led by EDF, with installation expected in 2017. EDF are also seeking permission to develop another site further offshore in the Mediterranean, which it will use for a first array of the VERTIWIND concept. Meanwhile, Enertag is still continuing a long-standing pursuit stretching back to 2005 for a 105 MW test site off Veulettes-sur-Mer, in the English Channel, which would mimic the Alpha Ventus approach to demonstrate several concepts on the same site. Consent has now been granted, but discussions with industry partners and government are still ongoing (Wind Power Offshore, 2013).

Germany

The GICON-SOF tension leg platform is set to become this world's first full-scale demonstration of a floating wind TLP concept when a 2 MW unit is installed in the German Baltic Sea in 2015. The site is located 21km off the coast of Zingst, in the German state of Mecklenburg-Vorpommern, and has been awarded consent by the State Department of Agriculture and Environment. GICON have also won a permit that allows them to apply for a network connection to feed power in via the Baltic 1 wind project. A nearby site has already been identified for a scaled-up 6 MW version of the concept.

Portugal

Principle Power took advantage of the existing electrical infrastructure from the from the Pelamis wave device demonstrator to install a 2 MW unit of their WindFloat device off the coast of Aguçadoura, Portugal, in 2011. There are plans to build out the site to add an additional 25 MW before 2020, with potentially an additional 125 MW beyond this. While the initial demonstration was located just 7-8km off the coast of Aguçadoura in 50m water depths, the second phase is expected to be further from shore, at 20km, in water depths of 85-100m.

Japan

Japan has extensive wind resource in deep waters relatively close to shore suitable for the deployment of floating wind farms. Two locations have been used to site full-scale floating wind demonstrations to date, at Fukushima on the east coast and Kabashima in the Goto Islands to the south-west of the country. Fukushima was selected more for iconic purposes more than any other, as a statement of intent to diversify energy sources in the wake of the nuclear disaster in 2011. However, the proximity of the site to the nuclear facility did ensure that the turbines could be connected to the grid without major upgrades. The site is relatively close to shore, at 30km, but given the plans to build-out the site an offshore floating substation was deemed to be required. Water depths of 100-150m are well-suited to floating platforms and enable the testing of a variety of concepts, with both spars and semi-submersible installed.

At just 1km from shore and water depth of 96-99m, the Kabashima site in the Goto Islands was an ideal location to test and monitor Toda Construction's hybrid concrete-steel spar buoy, which was installed in 2013. Despite being so close to shore, the site still receives average wind speeds over 9m/s and is also exposed to typhoons that hit the south of Japan; challenging conditions which help to validate the performance of the device. Nagasaki prefecture are hoping to build on the success of the first demonstration and the excellent conditions for testing of offshore devices by developing a major testing site for renewable marine energy, including floating wind and other marine power technologies. The centre will be loosely based on the European Marine Energy Centre (EMEC) off the north coast of Scotland, providing the necessary electrical infrastructure and onshore base for the testing of a variety of devices. Nagasaki hope to attract at least 13 regular customers by 2022.

USA

The USA also has significant potential for floating wind deployment, particularly along the west coast where deep water is prevalent. Coos Bay, off the coast of Oregon, is set to host the first full-scale demonstration of a floating wind turbine when five 6 MW units of Principle Power's WindFloat device is installed in 2017. The exact location of the array has yet to be decided, but a depth range of 24-365m in the area allows flexibility to install in the most cost effective location.

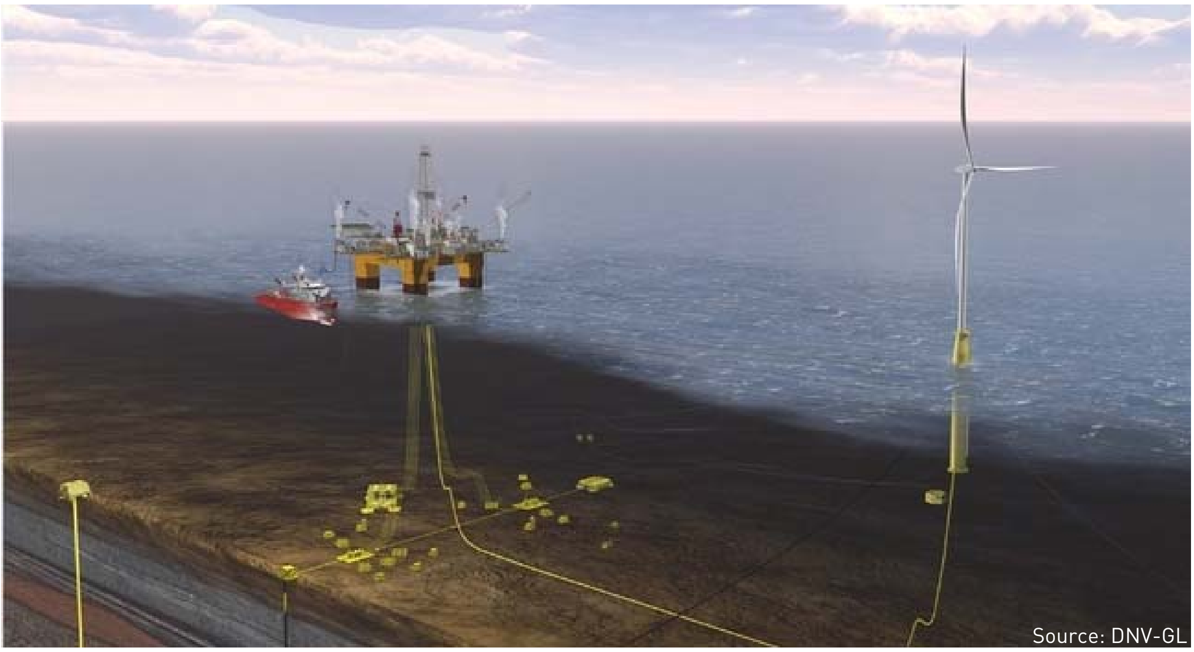
The Gulf of Maine has also be identified as a potential site for floating wind projects. A 1:8 scale 0.02 MW unit of the VolturnUS semi-submersible was the first grid-connected offshore wind turbine in the United States when it was installed in 2013 and there are plans to install two full-scale 6 MW units at a site 21km from shore in 61-110m water depth, with a lease granted to the University of Maine and site surveys already completed. Statoil have also investigated the possibility of installing their Hywind spar buoy concept in the Gulf of Maine. A lease was granted for the project but Statoil subsequently pulled out due to the uncertainty over obtaining a power purchase agreement.

2.11 Alternative Demonstration Opportunities

In response to the challenges to secure public funding and suitable test sites for full-scale demonstrations, DNV-GL have identified a possible alternative means of creating demonstration opportunities for floating wind devices, which involves using floating wind turbines to supply power to ageing offshore oil rigs for water injection processes used in enhanced oil recovery projects.

The retrofitted wind-powered water injection systems would be used to increase reservoir pressure and boost oil production through a variety of mechanisms ranging from straight raw seawater injection to a reverse osmosis process that pumps low salinity water into declining oil reservoirs. Conventionally, these water injection systems are powered by gas-fired turbines, which requires costly retrofitting of the offshore oil platform that can be constrained by available space and result in high fuel costs. Integrating water injection systems with floating wind turbines could therefore reduce capital and operating costs on oil platforms, as well as cut greenhouse gas emissions. The hybrid concept would also be mobile, meaning it could be used to access marginal oil fields and could also be moved to new project sites after an oil field had been fully exploited (DNV-GL, 2014).

DNV-GL are currently in the process of forming a 'Win-Win' (Water-powered Wind Injection) joint industry project (JIP) between players from both the oil and wind sectors which will test whether a combination of the two technologies can create synergies with mutual benefit for both industries. Principally, while the oil industry will be able to reduce costs, the wind industry will benefit from a new commercial market that removes the need for public subsidies. While this market may be relatively small, it could prove to be a vital lever to drive the development of new floating wind technologies, helping to demonstrate and de-risk floating wind devices, taking concepts from the prototype stage to commercial application.



Source: DNV-GL

3 Technology Review

In order to undertake a detailed review of the status and challenges of floating wind technology, the Carbon Trust issued a request for information (RFI) to all known designers of floating wind concepts. A set of baseline conditions were provided to allow for fair comparative analysis between concepts, consisting of a site at 100m water depth using 6 MW turbines (full details of the baseline conditions can be found in the Appendix). Responses were received from 18 designers, representing well over half the market and including the majority of the more advanced concepts under development. For confidentiality reasons, it is not possible to share data on individual concepts, hence the following analysis is largely based on a comparison between typologies (semi-submersible, spar-buoy, TLP, multi-turbine platforms and hybrid devices) and primary platform material (steel vs. concrete). The figures expressed constitute mean values, with variance expressed through the standard deviation of the data.

For the purpose of the analysis, caisson and barge concepts were grouped with semi-submersibles to avoid breach of confidential data sharing. Multi-turbine platforms and hybrid wind-wave devices were also grouped together, hereon referred to as 'multi/hybrid' platforms. For platforms supporting multiple turbines, relevant data is expressed on a per turbine basis. Likewise, for hybrid wind-wave devices, data expressed on a per megawatt basis includes the contribution of the wave energy component.

3.1 Design Characteristics

Platform:

- Most floating wind concepts can operate in water depths beyond ~35-50m (80-100m for spar-buoys), though the optimal depth is considered to be ~80-100m, where wave loading is typically lower and longer mooring lines are able to dissipate more of the forces acting on the structure.
- The lower platform weight of TLPs and lower grade steel used in spar-buoys result in a lower foundation CAPEX compared to semi-submersibles.
- Concrete platforms demonstrate a marked lower CAPEX than steel designs.

Moorings and anchors:

- The data suggests that longer and heavier catenary mooring chains used in semi-submersible and spar concepts are more expensive than the shorter and lighter tendons used in TLPs.
- However, concerns have been expressed over the fatigue life of tendons used in TLP concepts, which could increase costs.
- Anchor choice is largely dependent on geotechnical conditions, with suction piles and drag-embedded anchors more common in soft soils and a mixture of gravity, driven pile, and drag-embedded anchors most common in harder soils.
- Lighter drag-embedded anchors, used in semi-submersible and spar concepts, are considerably cheaper than the alternatives used in TLPs, which must be able to cope with greater vertical forces.
- Despite more expensive anchors, the reduced mooring cost results in a slightly cheaper overall mooring & anchoring system for TLPs.

Design modelling:

- Existing modelling software appears to be reasonably accurate, but there is scope for more advanced modelling tools that are able to conduct accurate coupled analysis of the full system, including the foundation, turbine, mooring, and anchors in variable met-ocean conditions.

Turbine:

- Most concepts claim to be 'turbine agnostic', capable of supporting most turbines in the current offshore wind market.
- Advanced control systems will need to be developed to maximise yield, reduce fatigue, and dampen floater motion, which can support a smaller platform size.
- Engaging OEMs early in the design phase will be critical to developing optimal integrated solutions.

Electrical system:

- Often neglected area which could be critical to the viability of floating wind.
- R&D efforts are needed to establish cost effective means of transmitting electricity back to shore in commercial-scale wind farms, namely by developing floating substations or offshore transformer modules and qualifying high voltage dynamic export cables.

Wake effects:

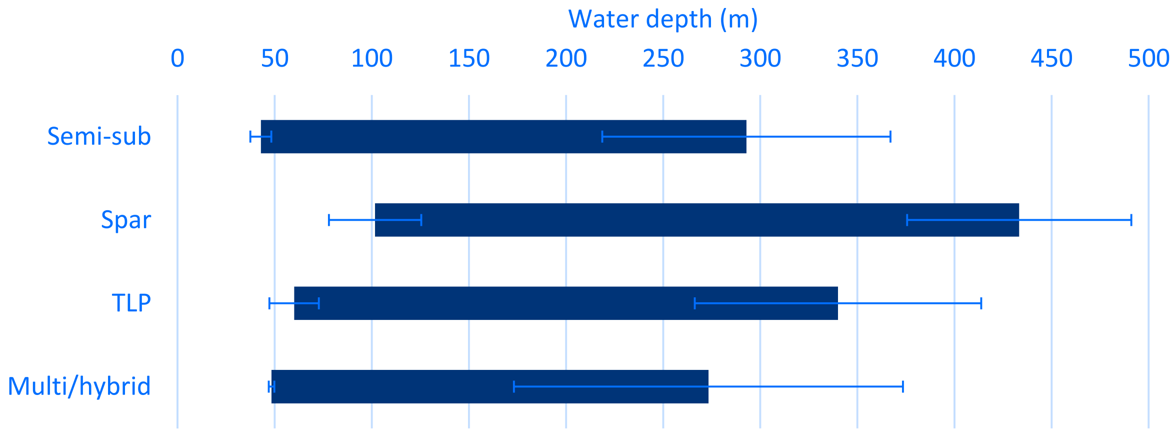
- Another neglected area which could impact greatly on LCOE.
- Urgent need to understand the impact of wake effects on commercial-scale arrays of floating turbines given the expected lateral movement of the floaters (semi-subs and spars).

Floating platform

Optimal water depth

The applicable water depth for most concepts begins at around 50m depth (figure 3.1.1). Semi-submersible and multi-hybrid platforms are able to operate at slightly lower depths than others, due to the reduced draft of the floaters; TLPs require slightly deeper water due to the loads placed on the mooring and anchoring system in low water depths; and spars tend to require at least 100m depth due to the large draft required. Spars are also able to operate in deeper waters than the other concepts, at up to 500m, while TLP, semi-submersible, and multi/hybrid platforms can operate in depths up to 400m. Application in even deeper waters is expected to be possible, but will lead to increased costs due to the size of the longer mooring lines. The optimal depth for most platforms is expected to be in the 100-150m range, where there is sufficient length and buoyancy on the mooring lines to reduce the loads placed on the mooring and anchoring system, but before the length of the moorings begin to add significantly to material costs due to the additional mooring length required.

Figure 3.1.1. Application of floating platforms by water depth



Platform weight

Structural weight is a large cost driver for floating wind platforms and minimising the amount of steel or concrete used in the platform is a key consideration for designers. Due to the vastly greater mass of concrete compared to steel, figure 3.1.2 below only includes data from concepts with steel as a primary material. There was insufficient data from concrete platforms to present the data by typology without infringing on confidentiality. The range of pre-ballast weight for all concrete structures ranged from ~2400-8700 tonnes.

Unsurprisingly, the heaviest structures are the multi/hybrid platforms, largely driven by the additional weight of the wave energy device. However, it should be noted that the multi-turbine platforms analysed were at the lower end of the range, in line with conventional semi-submersibles on a per turbine basis. Of the three dominant typologies, semi-submersibles are typically the heaviest, due to the large size of the structure required to maintain buoyancy and stability, weighing in at just under 2000 tonnes per unit. Spars are also expected to derive a high structural mass.

While some low values in the data imply a significantly lower mass than semi-submersibles, the average for the more mature spar concepts is at the higher end of the range given, on par with semi-submersibles. While spar-buoys are very large structures, the majority of their weight is provided by the ballast added during installation (figure 3.1.3), which will not have a major bearing on the overall cost of the structure. TLPs are considerably lighter than their counterparts, weighing in at just over 1000 tonnes on average, and requiring no added ballast.

Figure 3.1.2. Platform weight, pre-ballast, by typology (steel concepts only)

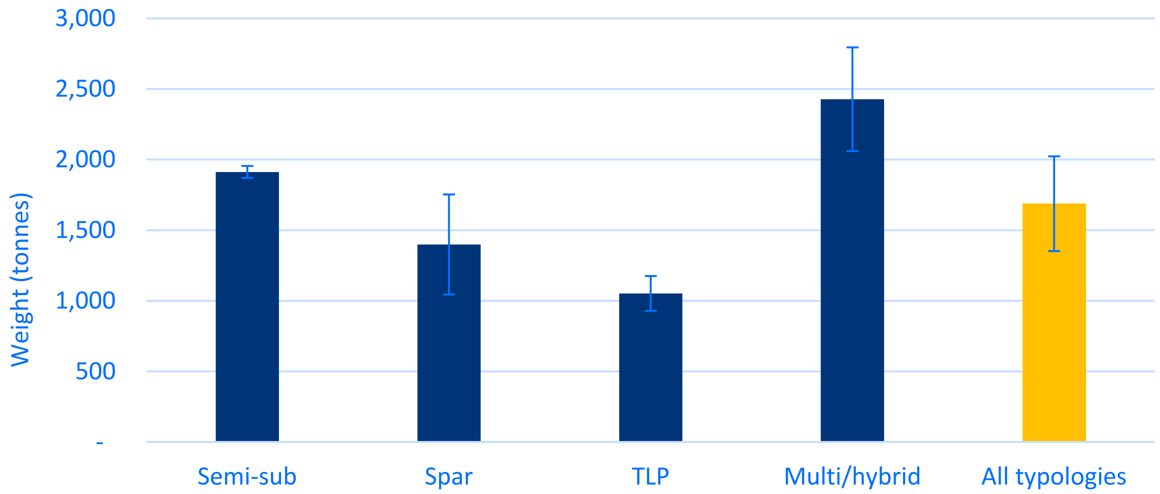
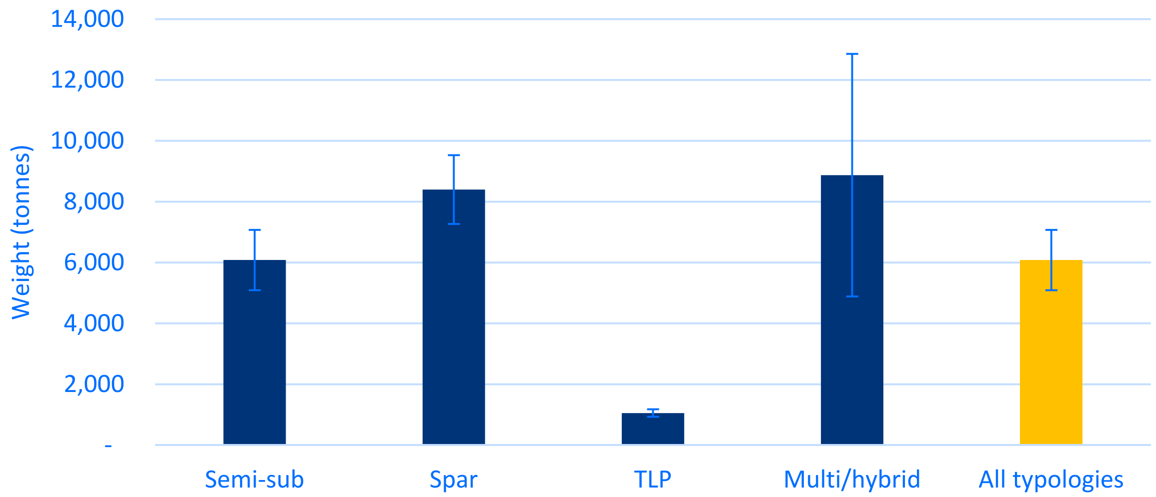
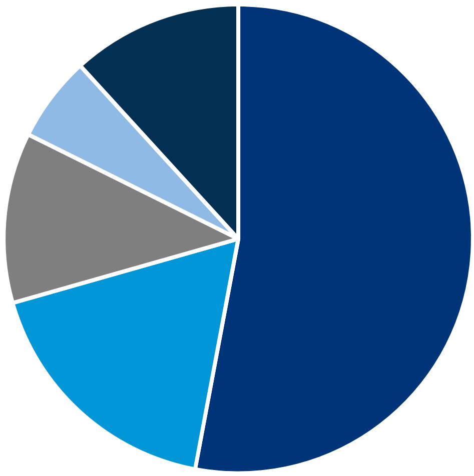


Figure 3.1.3. Platform weight, post-ballast, by typology (steel concepts only)



Most concepts adding ballast use water, either independently or with a mixture of water with rock, sand, or concrete (figure 3.1.4); all of which are available at low cost. Increasing the share of ballast weight versus the steel or concrete of the primary structure is therefore desirable, so long as this does not compromise the performance of the system.

Figure 3.1.4. Ballast type



Platform cost

Cost analysis differentiated steel from concrete designs as it was deemed that this would distort the outcomes. Concrete concepts are therefore not included in the typology averages below, but are grouped in a concrete-only set of data. The cost data assumes a commercial-scale wind farm (>300 MW). It should be noted that the cost data consists of estimates submitted by designers, which have not been validated and therefore a carry a certain degree of uncertainty, particularly given that most of the concepts assessed have yet to be built.

According to the data received, the most expensive concepts are the multi/hybrid platforms, due to the large volumes of steel required and additional expense of the wave energy units for certain concepts (figure 3.1.5 & figure 3.1.6). Within the main three typologies, the relationship with platform weight is less clear, largely attributed to the different grades of steel used. Spar-buoys appear to be the cheapest, attributed to the lower grade steel that can be used (similar to fixed-bottom monopiles) and ease of fabricating the simple structures using well-established steel rolling techniques. Again, some low values in the data bring the average down, and analysis of only the more mature concepts indicates a higher foundation cost, on par with TLPs.

Semi-submersible and TLP concepts typically require higher grade steel (similar to fixed-bottom jacket foundations) to ensure structural integrity, which is more expensive and more challenging to fabricate in more complex semi-submersible and TLP designs. For TLPs, the smaller structural dimensions result in a lower cost platform than semi-submersibles, whose large weight makes them the most expensive of the three main typologies.

Figure 3.1.5. Platform cost by typology

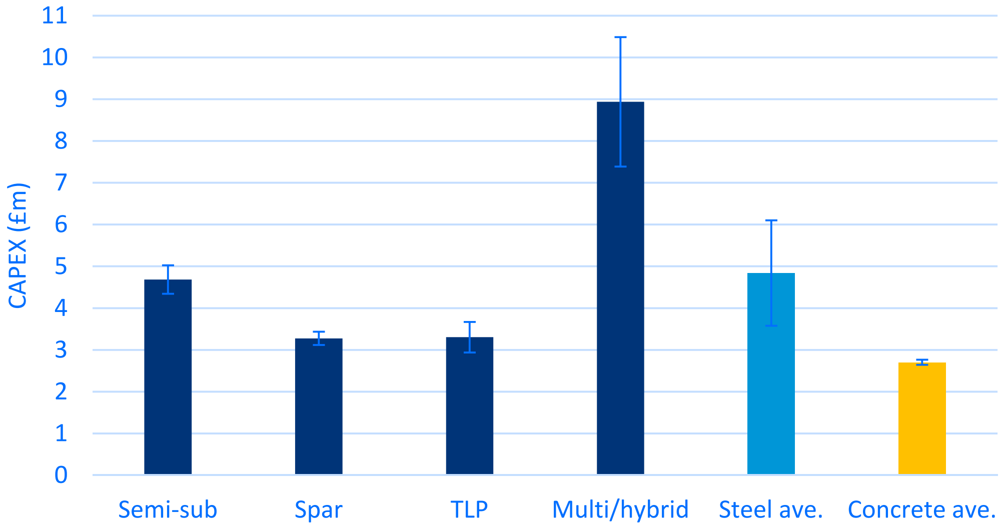
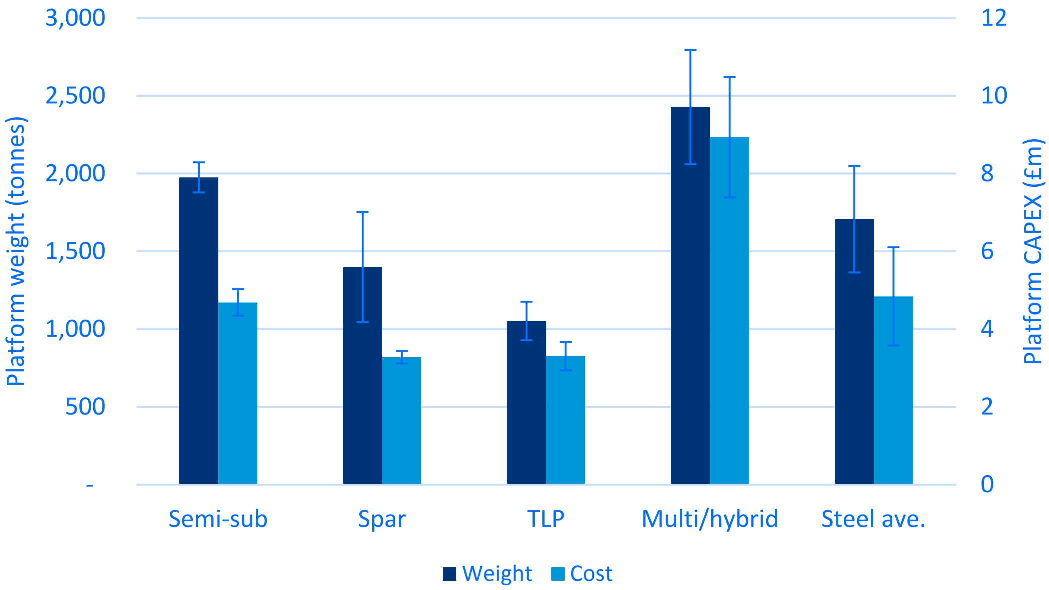


Figure 3.1.6. Platform weight vs. cost (steel only)



There appears to be a trade-off between reducing structural mass and maintaining low steel costs, as evident in figure 3.1.7, which expresses the implied cost per tonne of the different typologies. Steel used in spar-buoys has the lowest cost per tonne (even more pronounced when only considering more mature concepts), but the larger structural mass results in a total platform cost similar to the smaller TLPs concepts, which require more expensive higher grade steel. Nevertheless, it remains broadly true that reducing the weight of the floating platform can contribute significantly to lower capital expenditure (figure 3.1.8).

Figure 3.1.7. Implied cost per tonne

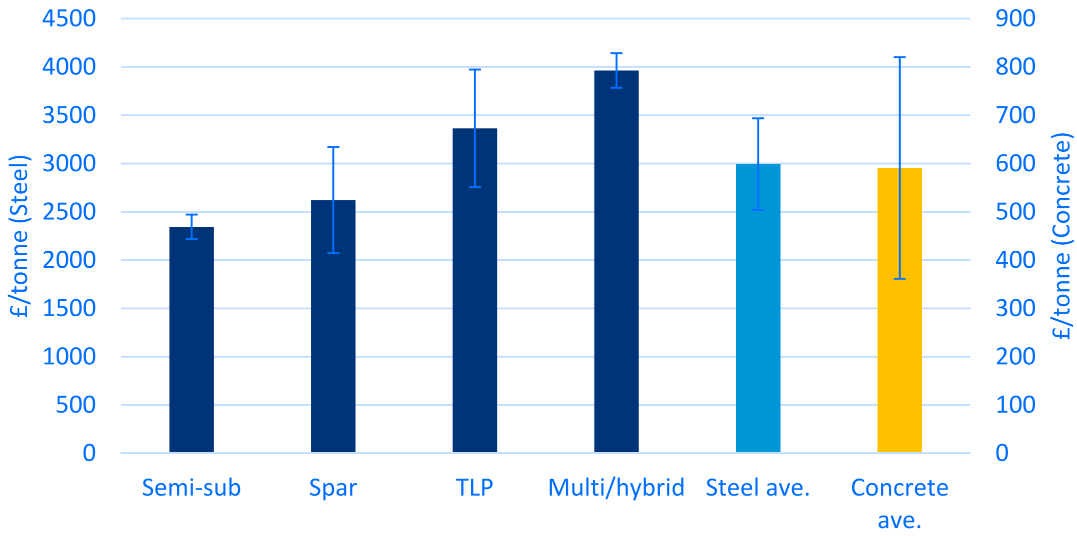
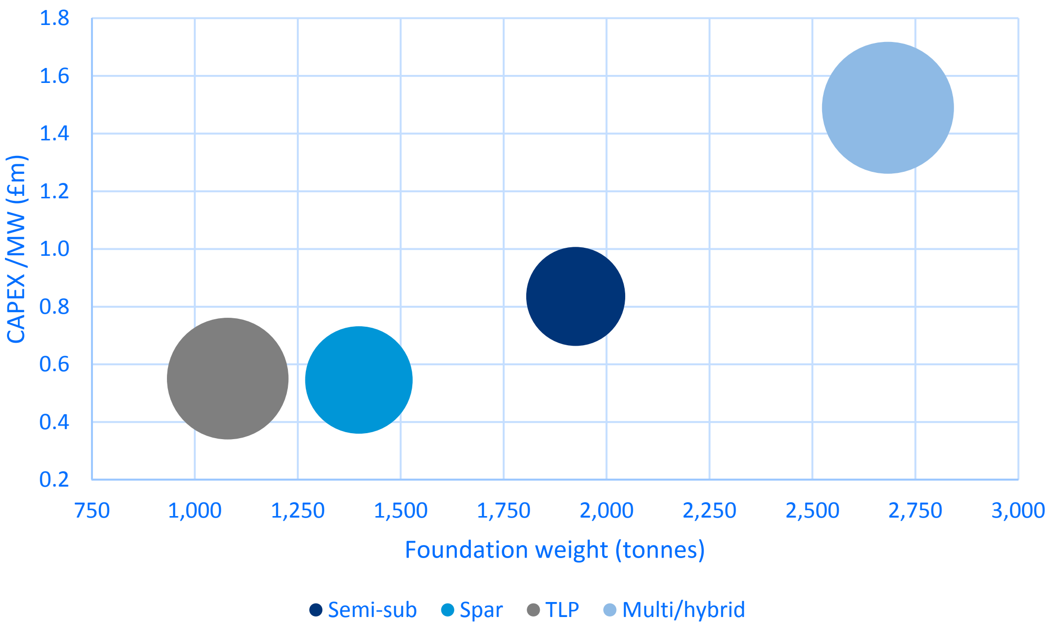


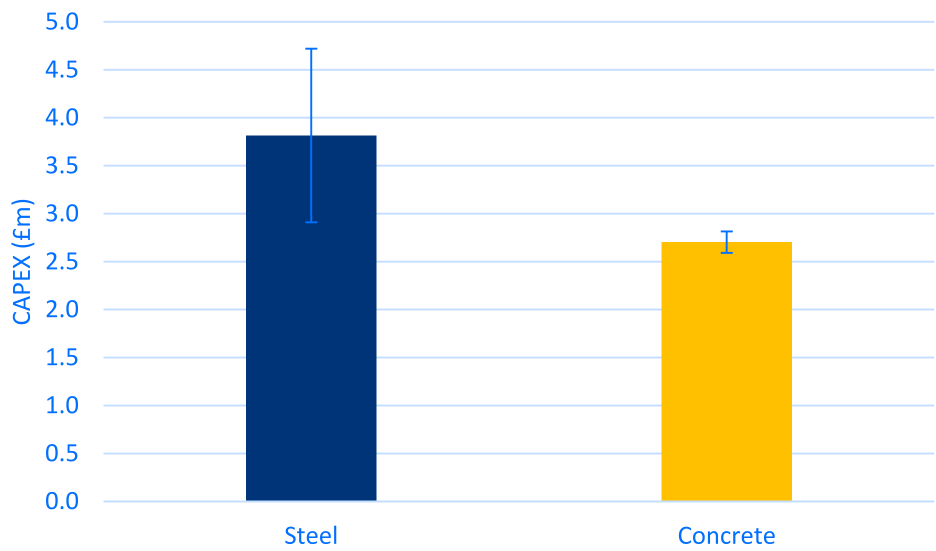
Figure 3.1.8. Platform cost by weight (steel only)



N.B. Bubble size corresponds to the cost per tonne

A comparison between concepts also infers a lower CAPEX for concrete platforms, versus their steel counterparts (figure 3.1.9). While this is not necessarily always the case, and the primary material will often be dictated by the design and local capabilities for a given project, there is a strong argument for moving away from the dominance of steel as the primary material for the floating platform. Concrete also brings benefits with regard to increasing local content and reduced maintenance, since it is less prone to the effects of corrosion than steel foundations. Although given the dominance of steel to date there is less experience in the large-scale fabrication of concrete structures for the offshore wind industry, and lead times need to be carefully assessed to ensure that structures are delivered on time and on budget. Some concepts (e.g. IDEOL, Hywind) have been designed for either steel or concrete construction, which gives greater flexibility to developers depending on the local capabilities and infrastructure near to site.

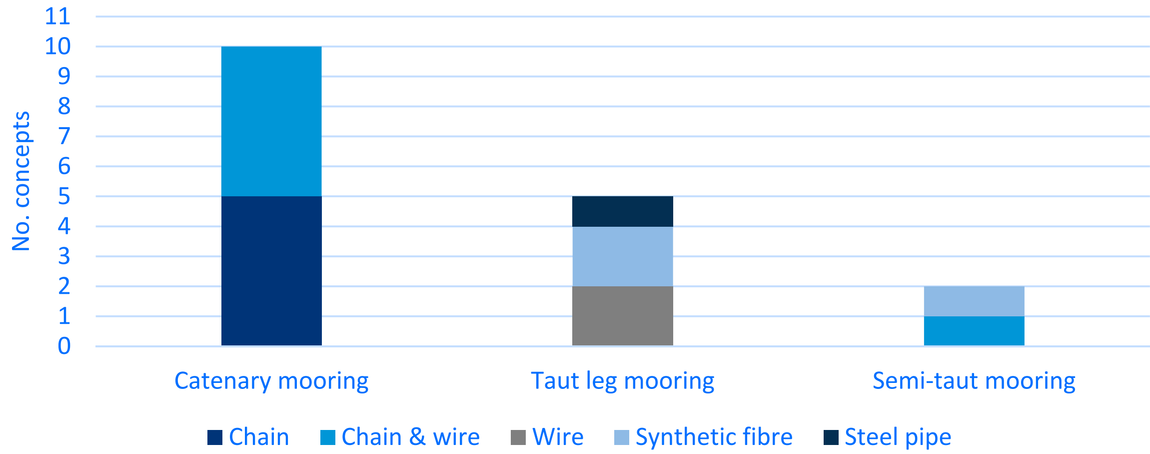
Figure 3.1.9. Platform cost by primary material (semi-sub, spar, TLP only)



Moorings

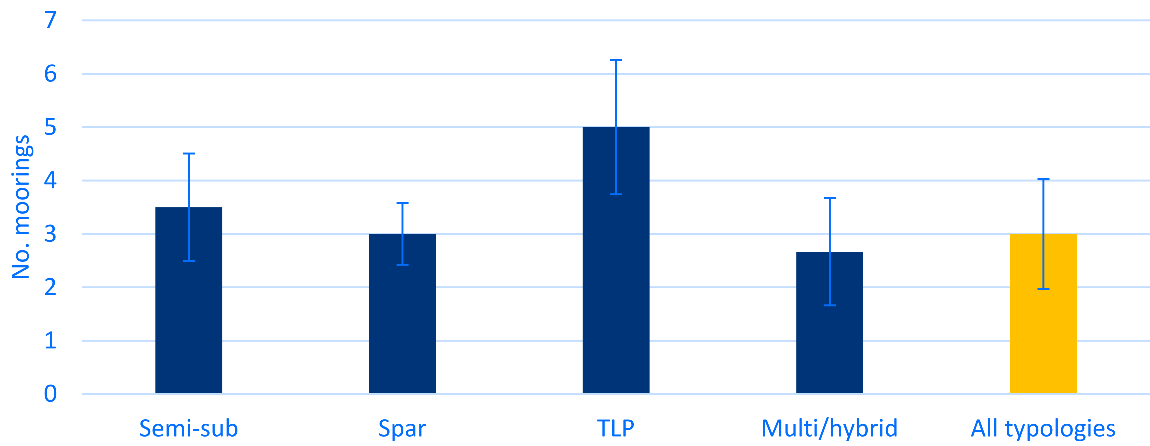
An overview of the different mooring configurations used for floating platforms is included in section 2.2. Carbon Trust analysis of the different concepts in the market confirms that catenary mooring configurations are the most common, with steel chains or chain & wire moorings used to secure semi-submersible, spar, and multi/hybrid concepts (figure 3.1.10). Semi-taut moorings are also used on some semi-submersibles, consisting of either synthetic fibres or chain & wire moorings. For TLPs, taut-leg mooring tendons are used, typically comprised of synthetic fibres or steel wire.

Figure 3.1.10. Mooring configurations and types used for floating platforms



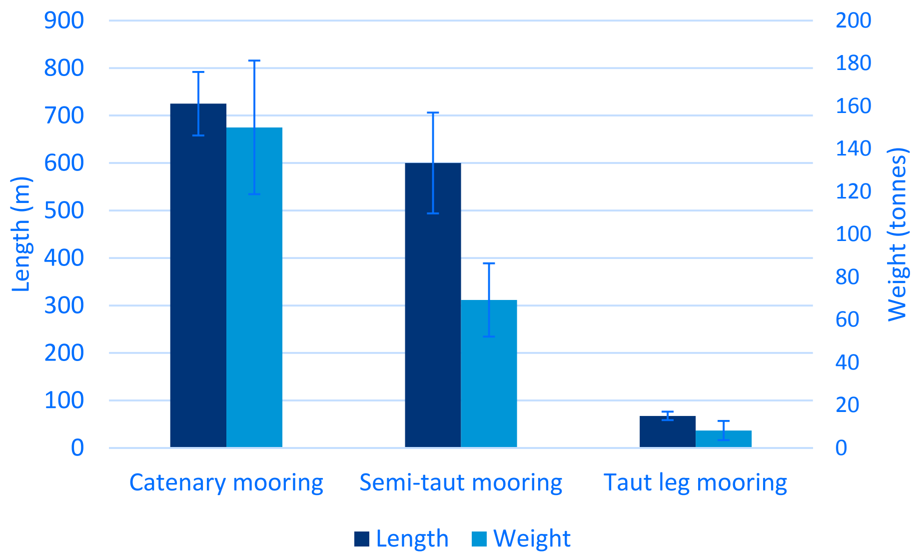
Most concepts require at least 3 mooring lines in order to provide sufficient load distribution, limit motion, and allow for redundancy in the mooring system in case of a failure. Economies of scale enables multi/hybrid concepts to use fewer moorings per turbine (figure 3.1.11). Conversely, TLP concepts require more mooring lines than other concepts, largely due to the need to maintain equal load distribution around the structure and to dissipate the high forces between more mooring lines and anchors. Fewer catenary moorings are required in semi-submersible and spar concepts because the platform is already buoyancy stabilised, and the long moorings lines are able to withstand the forces placed on them. More mooring lines can add greater redundancy to the system, and a number of concepts have evolved over time to incorporate more tethers to guard against the risk of mooring failure. This trend may be expected to be seen in more concepts as they mature.

Figure 3.1.11. Average number of moorings per turbine



As expected, catenary moorings are longer and heavier than semi-taut and taut moorings (figure 3.1.12). It should be noted that the reduced weight of the semi-taut moorings is due to the use of lightweight synthetic fibre for some concepts, but the weight would usually be expected to correspond with length, much like catenary moorings. The use of lightweight synthetic fibres is also evident in taut leg moorings, where the weight of the mooring lines is considerably lower.

Figure 3.1.12. Mooring length and weight per unit

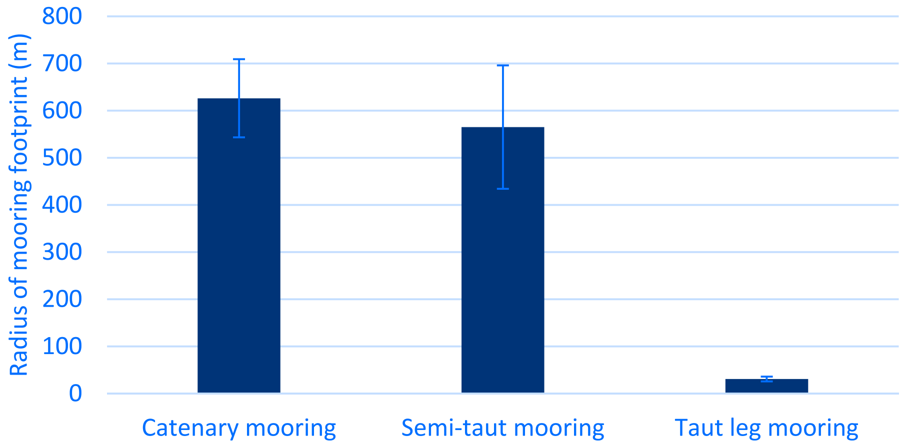


The longer mooring lines in catenary and some semi-taut configurations result in a larger mooring footprint for semi-sub, spar, and multi/hybrid concepts (figure 3.1.13). This could have implications for consenting given the greater impact on the seabed. In particular, with catenary moorings the lower sections of the chains will rest on, and therefore disrupt, the seabed. There may be scope to conduct studies to assess the true environmental impact of mooring and anchoring systems.

Another concern with longer mooring lines with a large footprint is the amount of lateral motion that this will allow, which could be up to 50 metres in concepts with catenary mooring configurations. While this may not be a major issue for single turbine demonstrations or small arrays, in commercial scale windfarms this could impact on the wake effects through the array, if turbines drift in to areas of increased turbulence and lower wind speeds. The difficulty in modelling the expected yield may also increase uncertainty and impact on financing for the project.

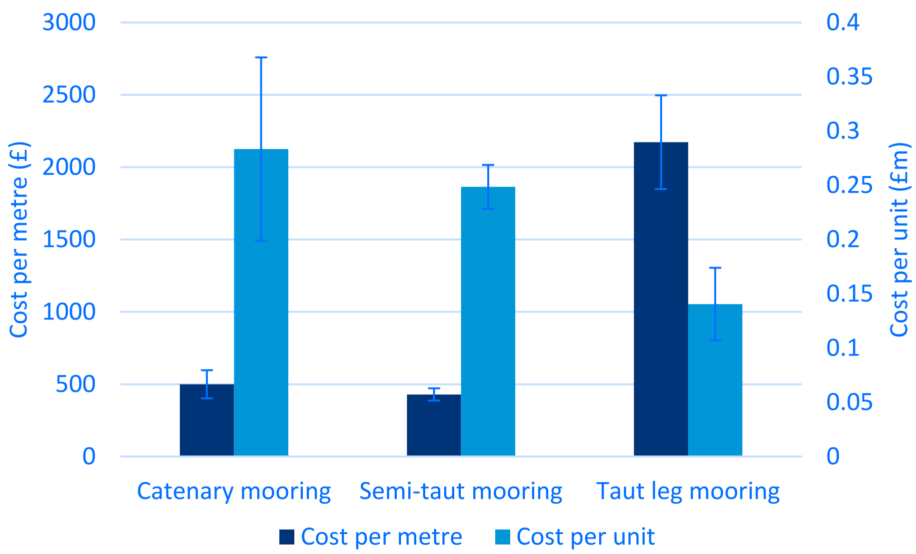
While the taut-leg moorings in TLP concepts are unlikely to experience significant lateral movement, they are more susceptible to yaw motion. With only vertical tendons securing the structure, the platform will have little yaw stiffness to take up non-symmetrical loads, which could increase rotational motion (around the vertical axis). Understanding the degree of motion expected and its impact on yield and mooring integrity will need to be a focus for TLP designers.

Figure 3.1.13. Radius of the mooring footprint



Although shorter in length, taut-leg tendons need to be able to withstand large vertical forces and are significantly more expensive on a per metre basis (figure 3.1.14). Nevertheless, the shorter mooring lengths still yield a lower cost per mooring line and per turbine in taut-leg mooring systems. It should be noted, however, that this does not include the cost of mooring installation, which is expected to be higher for taut-leg moorings.

Figure 3.1.14. Mooring cost per metre and per unit by configuration



Mooring type reveals a similar trend. Despite a heavier mass per metre, chain and chain-wire mooring lines, typically used in catenary configurations, are significantly cheaper per metre; meanwhile, the lightweight synthetic fibre tendons used in taut-leg configurations are more expensive on a per metre basis (figure 3.1.15). Wire moorings are both heavier and more expensive on a per metre basis. However, the net effect per mooring line is a higher cost for the longer chain and chain-wire moorings, and a lower cost for shorter taut-leg synthetic fibres and wires (figure 3.1.16). Despite more taut-leg moorings typically required per turbine, total CAPEX is still lower for tension leg systems (figure 3.1.17). It should be noted, however, that synthetic fibres have yet to be demonstrated in floating wind and may experience challenges in terms of creep, non-linear stiffness, and wear and tear, which could drive up costs.

Figure 3.1.15. Mooring weight per metre and cost per metre, by type

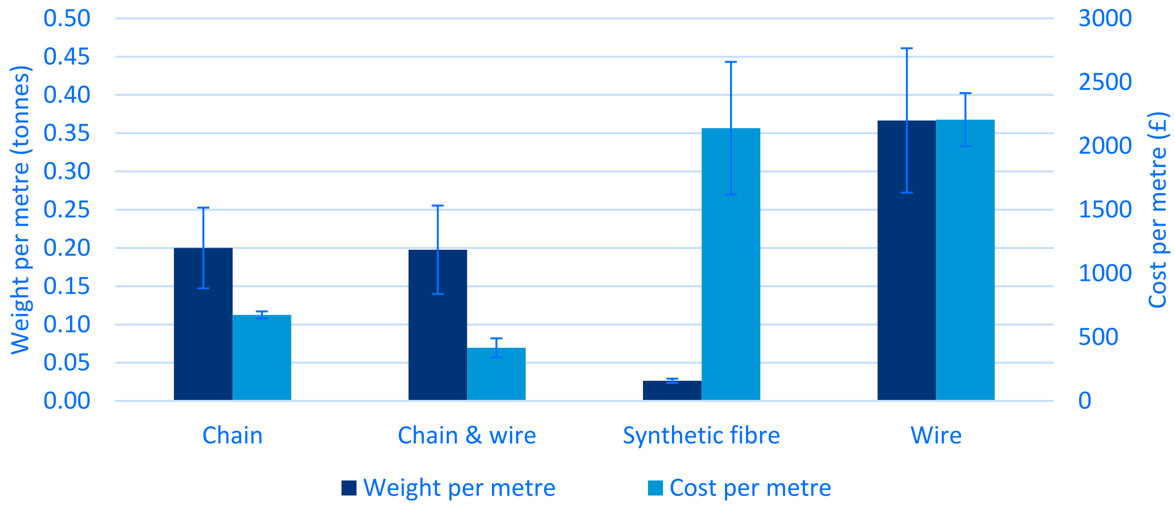


Figure 3.1.16. Mooring length and cost per unit, by type

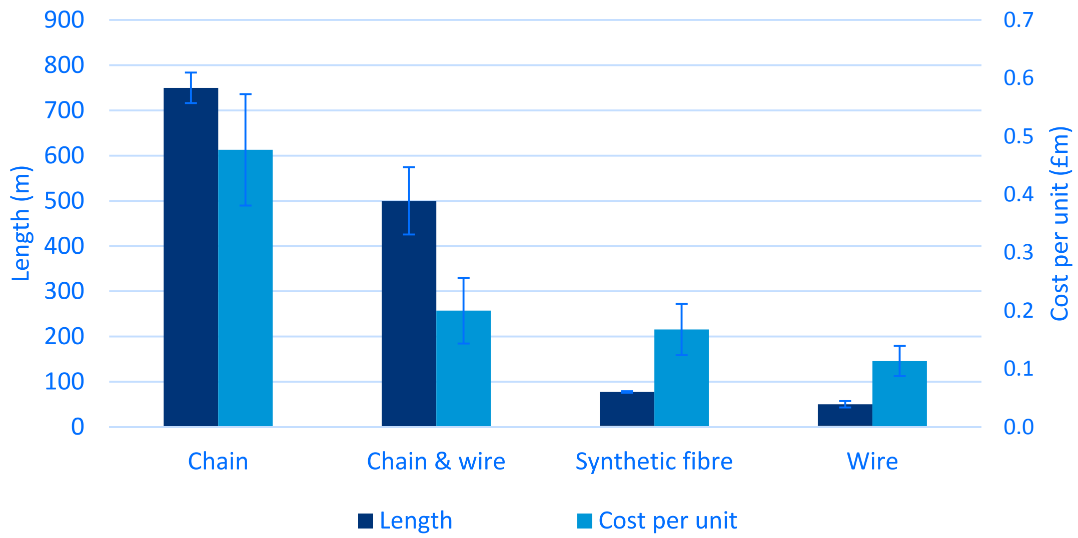
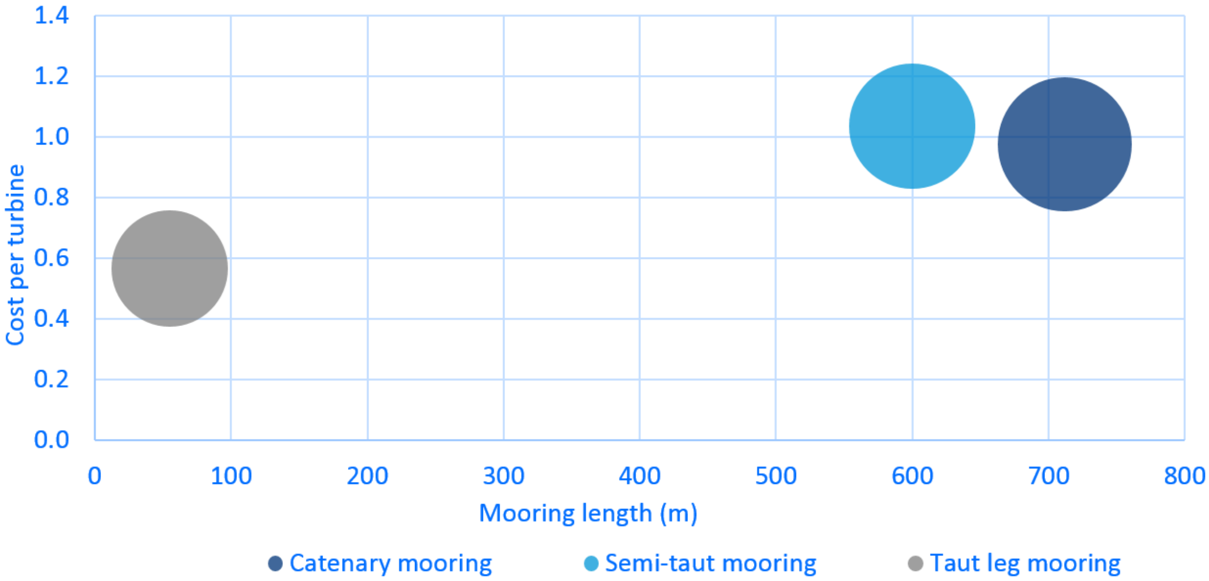


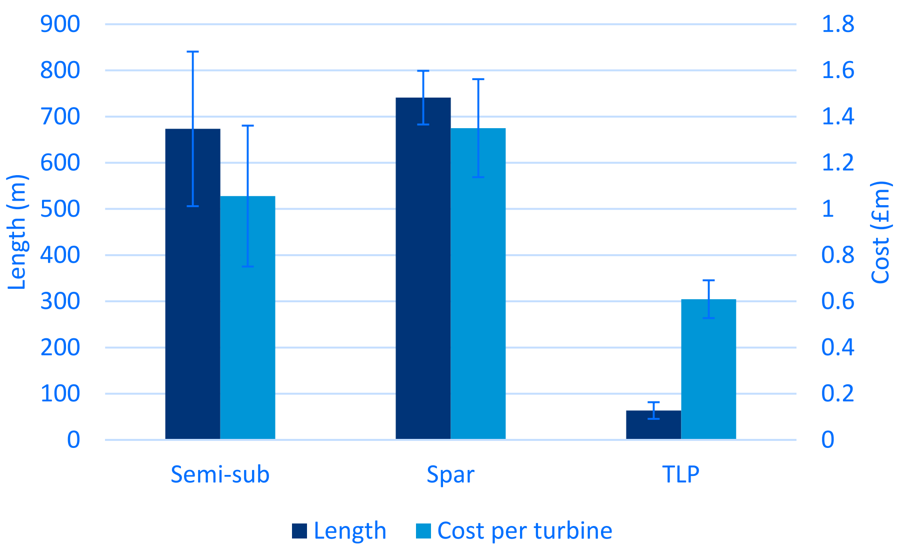
Figure 3.1.17. Mooring cost per turbine by length



N.B. Bubble size = Mooring cost per unit

The trends observed generally translate to the respective floater typologies. Semi-submersibles and spar-buoys have long mooring lines with a high unit cost, and TLP concepts have considerably shorter mooring lines which, despite a higher cost per metre, are still cheaper per turbine than the mooring lines used in the other typologies (figure 3.1.18). Although there is considered to be greater uncertainty associated with TLP moorings due to the lack of operational devices, compared to semi-submersible and spar-buoys, which have been demonstrated in a number of prototype demonstrations. Data for the multi-turbine and hybrid platforms veers from the expected relationship with semi-submersibles, with very low costs given the length of the mooring lines used. It is assumed that this data is anomalous and has therefore been excluded from the analysis.

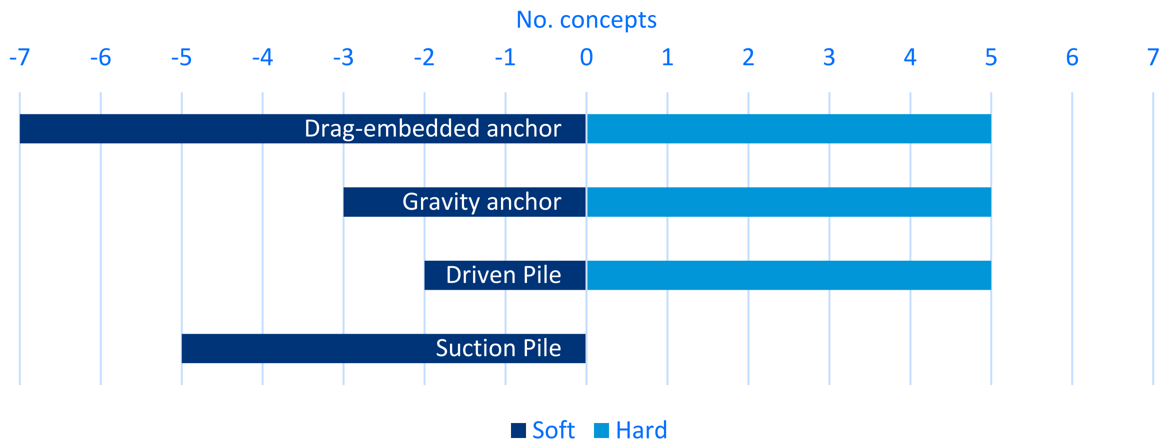
Figure 3.1.18. Mooring length and cost per turbine, by floater typology



Anchors

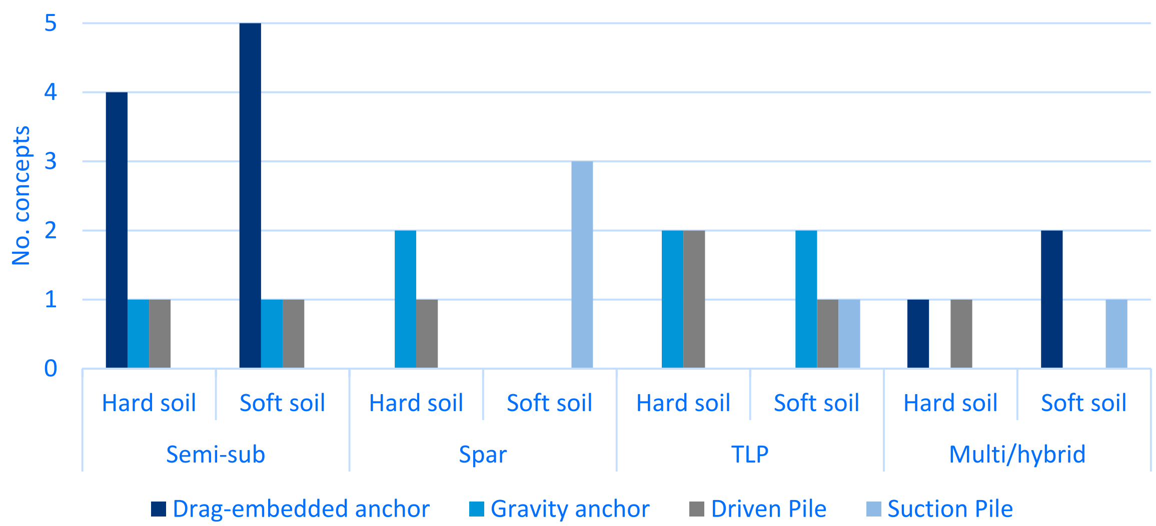
An overview of the different mooring configurations used for floating platforms is included in section 2.2. The choice of anchor will always require detailed analysis on a site-by-site basis; however, for the purposes of this study, designers were asked to indicate the preferred anchor type in both 'hard' and 'soft' soil conditions. Drag-embedded anchors are the most widely used, in line with the prevalence of catenary mooring configurations, particularly in soft soil conditions (figure 3.1.19). In tougher soil conditions there is a shift to using gravity anchors and driven piles due to the difficulty in penetrating the seabed with drag-embedded anchors. This trend is even more acute for suction piles, which were a common choice in soft soils, but cannot be operated in hard seabed conditions.

Figure 3.1.19. Anchor type by soil density



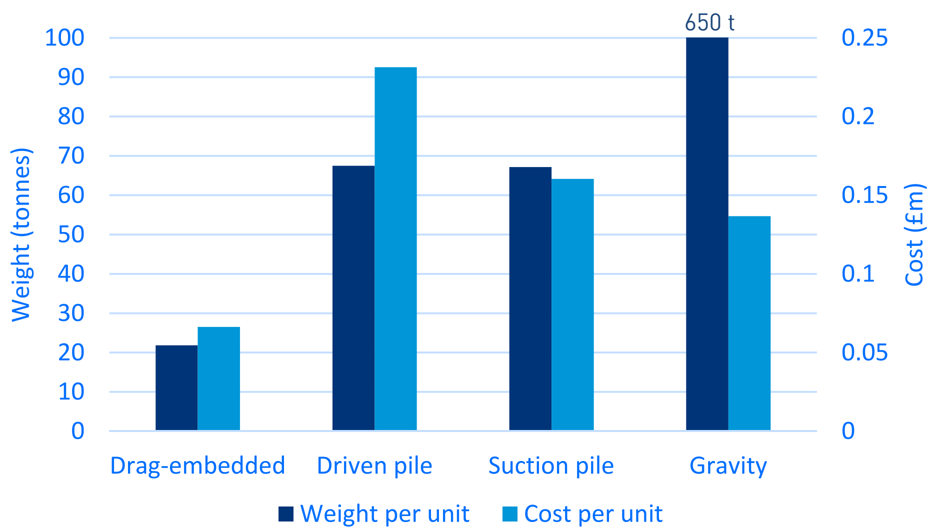
Drag-embedded anchors are only used by concepts with catenary mooring configurations (figure 3.1.20), due to the level of horizontal loading on the anchors, which drag-embedded anchors are well-equipped to cope with. Conversely, anchors used in TLP designs require gravity and driven anchors, with suction anchors also an option in soft soils, in order to contend with greater vertical loading.

Figure 3.1.20. Anchor type by floater typology



Anchor cost is closely tied to weight, and therefore the amount of steel used (figure 3.1.21). Drag-embedded anchors are considerably lighter and cheaper than the heavier and more expensive driven and suction piles. Gravity anchors are extremely heavy, but the availability of cheap concrete means that the cost is fairly modest. However, it should be noted that this does not include the cost of anchor installation, which could alter the cost competitiveness of different anchor solutions. For example, gravity anchors may incur higher costs if an additional vessel is needed to install the ballast.

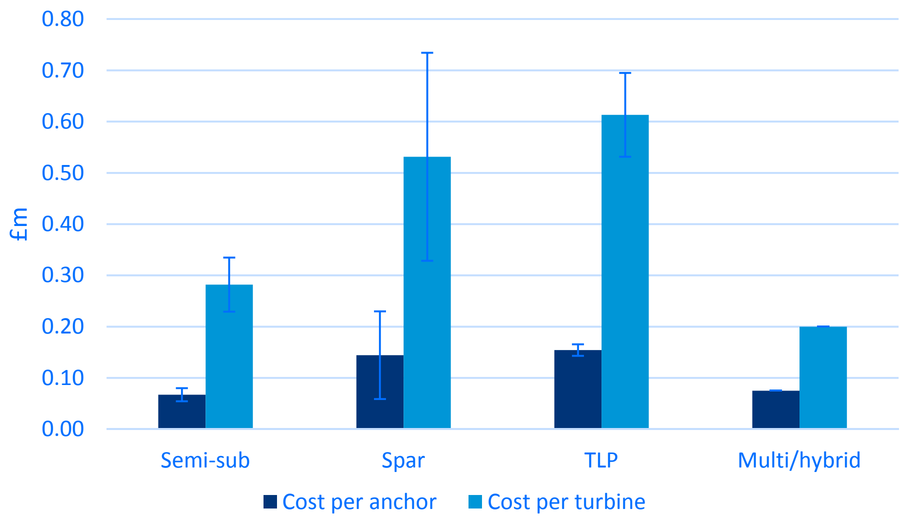
Figure 3.1.21. Anchor weight and cost per unit, by anchor type



N.B. Average weight per unit for gravity anchor is 650 tonnes.

Anchor costs are generally higher for TLPs, both on a per unit and per turbine basis, largely attributed to the need to withstand high vertical loading and maintain platform stability (figure 3.1.22). Conversely, the drag embedded anchors used in semi-submersible and multi/hybrid concepts are demonstrably cheaper than other alternatives. Anchor costs for spar-buoys would be expected to be in line with this, but the driven, suction, and gravity anchors assessed in this analysis derive higher costs.

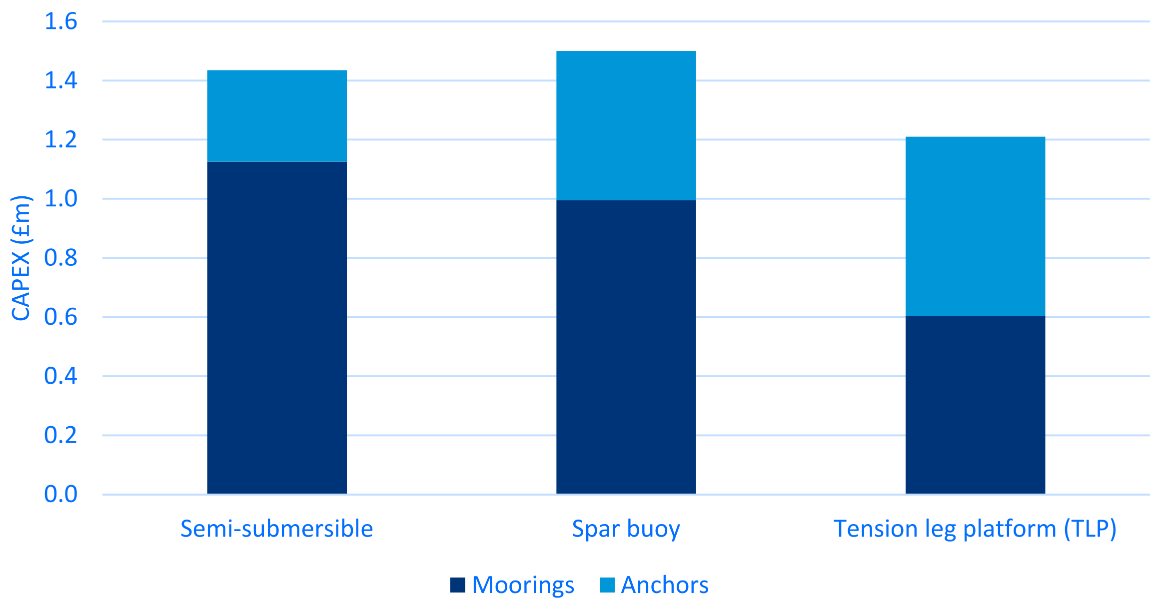
Figure 3.1.22. Anchor cost per unit and per turbine, by floater typology



Combined mooring & anchoring system

The net effect of the cost of mooring and anchoring systems for the different typologies is shown in figure 3.1.23. Semi-submersible and spar-buoy concepts are expected to attain a similar total CAPEX, and this is broadly evident in the data, bar slightly higher anchor costs for spar-buoys driven by the type of anchor type. For semi-submersible and spar-buoy concepts adopting a comparable catenary mooring configuration and drag-embedded anchors, the overall cost is similar. Unlike semi-submersible and spar designs, where the moorings are the biggest cost driver, for TLPs a far higher share of the overall cost is applied to the anchors, which need to withstand large vertical loads. However, despite higher anchor costs, TLP concepts yield a lower total CAPEX due to the lower mooring costs, which are driven by the considerably shorter tendon length of the taut mooring tendons. Again, it should be reinforced that the data constitutes estimates, and actual costs may vary in practice.

Figure 3.1.23. Total CAPEX for the mooring & anchoring system



Design modelling

A number of different software packages are available to help designers to test and optimise their concepts. The majority of designers are able to integrate a number of key facets, including the floating platform, mooring and anchoring system, turbine, and wind and wave loading. However, there appears to be a modelling gap around the geotechnical conditions at a site (figure 3.1.24), which greatly impacts the mooring and anchoring system that needs to be adopted. Without the ability to model anchor-geotech dynamics, there is a risk that this will result in conservative and more expensive designs. It should be noted that some designers are able to model the anchors separately from the rest of the structure, as deformation of the anchor is not considered to have a significant impact on the mooring system. However, given the need to improve fully integrated modelling, as well as the diversity of soil conditions encountered between different sites around the UK and further afield, this should be a key consideration for software developers.

Figure 3.1.24. Level of integrated design possible using existing design software

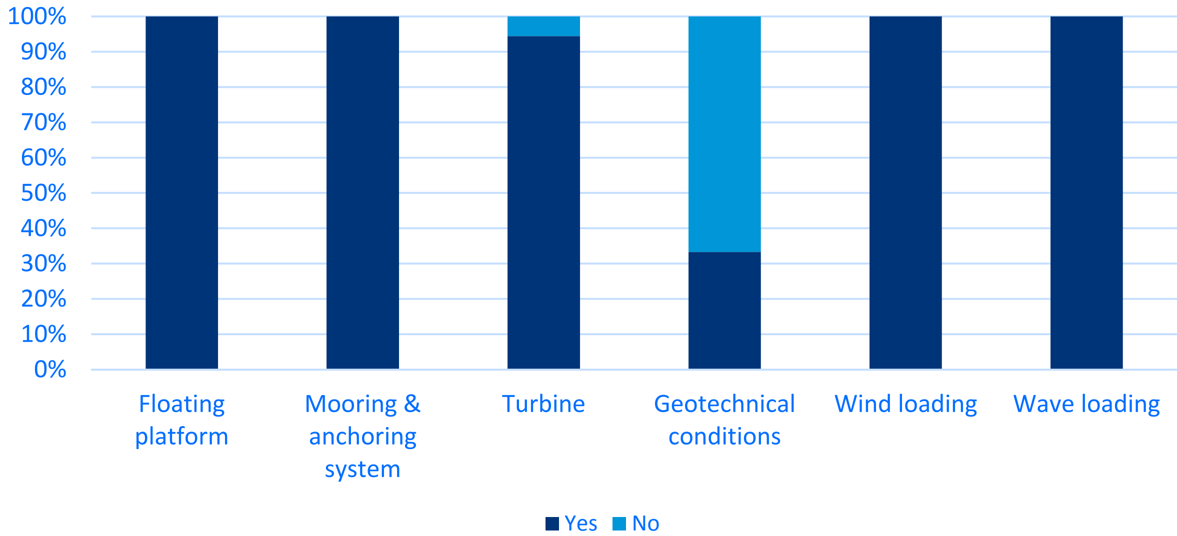
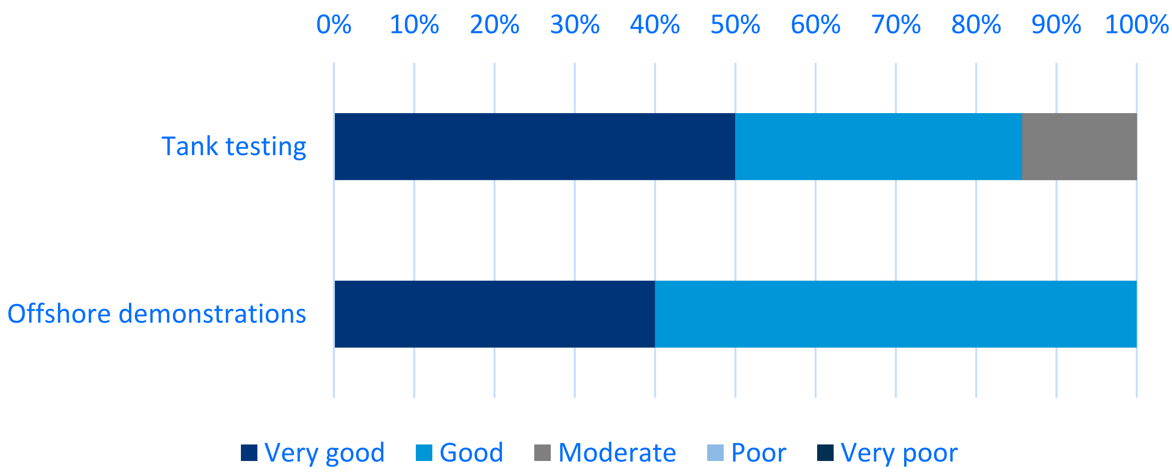


Figure 3.1.25 gives an indication of the accuracy of the software currently available. Responses are generally very positive, with a good or very good agreement between design models and testing. However, industry modelling experts have suggested that some platform designers are not accurately capturing the holistic system response (e.g. coupled analysis of the turbine, platform, moorings, and anchors), supporting the claim that optimal floating systems may not be turbine agnostic, and that further work is needed to improve modelling tools. This is hardly surprising given the nascent state of the industry and scarcity of full-scale demonstration to date. The need for further work in this area is already being addressed to some extent by DNV-GL, who are due to kick off a joint industry project in 2015 which will create a set of industry guidelines on coupled dynamic analysis of floating wind turbines. However, while the DNV-GL JIP will focus on procedures, it will also be necessary to analyse the performance of software tools, with closer integration between offshore demonstrations, tank testing, and numerical models.

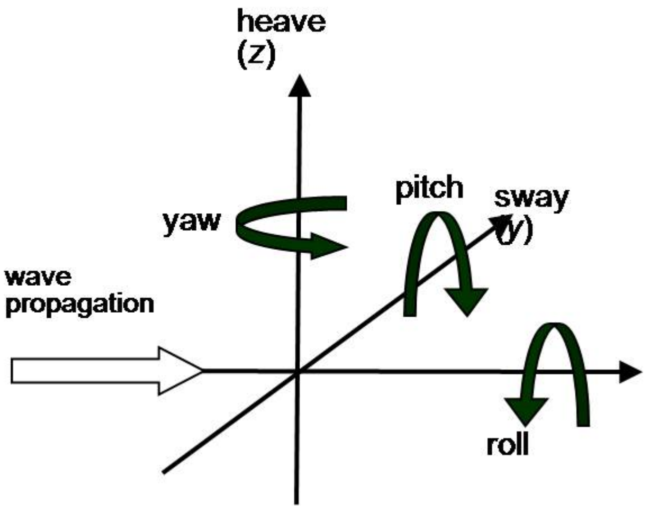
Figure 3.1.25. Level of agreement between modelling and testing



Floater motion

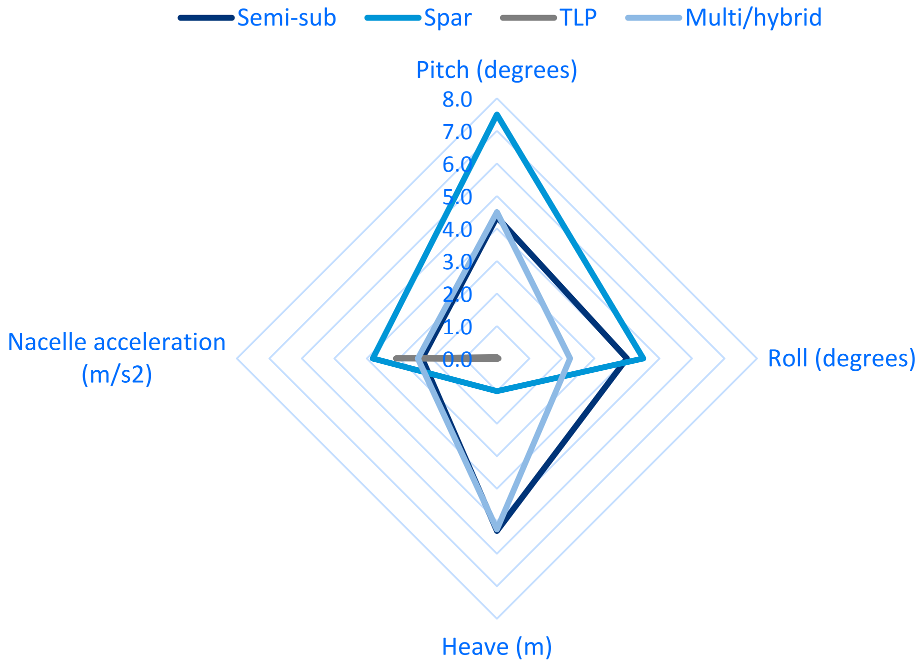
Floating wind platforms are designed to restrict floater motion to certain limits, largely in order to limit the amount of turbulence and acceleration at the nacelle. For a floating wind structure, limiting the amount of heave, pitch, and roll is key to reducing nacelle accelerations (figure 3.1.26). The data submitted for the different concepts analysed suggest that nacelle accelerations are restricted to less than 4 m/s^2 in all cases, which allows the use of conventional fixed-bottom turbines with only relatively small design modifications. However, developing appropriate control systems to maximise yield and dampen floater motion will be critical to improve reliability and support reductions in platform size.

Figure 3.1.26. Forces acting on a floating wind structure to induce motion (Univ. Lancaster)



Noticeable trends are observed between concepts with regard to floater motion (figure 3.1.27). Namely, motion is limited most in TLP concepts, where the taut tension legs restrict pitch, roll, and heave significantly. Semi-submersible and multi/hybrid concepts show similar characteristics to each other, with moderate pitch and roll but significantly more heave than other concepts, due to the increased buoyancy of the platform over a relatively large surface area. Spars, conversely, have limited heave, due to the large weight of the lower sections of the spar, which provides ballast stability by ensuring that the centre of gravity is significantly below the centre of buoyancy. However, the elongated shape of the spar design can make it more susceptible to pitch and roll. Although existing demonstrations have performed well and achieved high levels of availability and high capacity factors, limiting floater motion should be a focus for future R&D initiatives, engaging OEMs to improve cooperation with concept designers.

Figure 3.1.27. Level of floater motion permissible for floating wind concepts



Turbine

As the largest single component of the cost breakdown for floating wind projects and the source of electricity (and revenue) generation, the performance of the turbine warrants considerable attention. As well as maximising yield and power output, turbines will need to demonstrate high levels of availability. As noted above, turbine accelerations are expected to differ not just between fixed-bottom and floating platforms, but also between different concepts. Turbine-floater dynamics will impact heavily on the reliability and power output of the turbine and advanced control systems will need to be developed to minimise nacelle accelerations, particularly given the need to ensure high levels of availability over a 20-25 year lifetime. Blade pitch control can also help to dampen floater motions and support efforts to reduce platform size.

Most floating wind concepts under development claim to be turbine agnostic, such that they are able to accommodate any top-tier offshore wind turbine used on conventional fixed-bottom foundations. However, as noted above, the impact of the floater motions on the wind turbine means that design modifications are required and advanced control systems need to be developed for each foundation typology to achieve optimal turbine-platform interactions. Furthermore, concerns have been raised that the warranty agreements for existing offshore wind turbines would be invalidated if they were placed on a floating support structure. Engaging OEMs, certification bodies, and bank engineers will therefore be important to mitigate the risks associated with moving to floating technology.

The design of the floater platform and turbine in isolation, or even design modification late in the development process, are unlikely to deliver the most cost effective solutions. Rather, there is a critical need for integrated design of the full system, including the turbine, platform, moorings, anchors, and other auxiliary equipment. This can result in an optimised solution which reduces platform weight, improves turbine availability, reduces fatigue, and thereby results in a lower cost solution which reduces both capital and operational expenditure. An early example of this closer cooperation between OEMs and concept designers is evident in the collaboration between DCNS and Alstom to develop the SeaReed concept. It is expected that more partnerships will begin to emerge between floating platform designers and turbine manufacturers, with integrated solutions for the offshore wind market; though these partnerships are unlikely to remain exclusive, with a number of turbine options for different platforms more likely.

Nevertheless, all evidence to date suggests that turbines perform very well on floating platforms, with high load factors and availability rates in early demonstrators. The key indicator will be the long-term reliability of the turbines, particularly in relation to the amount of fatigue on the bearings and drive train, though this is just as relevant for fixed-bottom as it is for floating wind structures. R&D efforts to develop advanced control systems for floating wind systems, in combination with an improved understanding of the turbulence in floating arrays, will help to ensure high levels of reliability. Again, engaging OEMs early in the design process will be critical to ensure optimal integrated solutions are developed.

Electrical system

In addition to the core features of the turbine, floater platform, moorings and anchors, the electrical infrastructure for a floating wind project is a critical area which must be addressed, but is often overlooked in discussions about floating wind technology. While the technology focus to date has been on single turbine prototypes and small arrays, as wind farm capacity increases there will be a growing need for floating offshore substations and high voltage export cables to take the power back to shore. Only one floating substation has been installed so far, at the Fukushima test site in Japan in 2013. However, only limited attention has been directed to this area.

The large weight of the offshore substations places enormous pressure on the floating platform and results in a large and heavy platform, with associated high costs. The number of cables entering a floating structure could also cause challenges and increased risk perception. Particularly given the importance of the substation and the severe impact of power outages, conservative designs are likely. Optimising the platform design will therefore be critical to the cost competitiveness of floating wind, reducing the steel content in line with transformer platforms used in fixed-bottom projects. Given the importance of the substation and additional risk of moving to a floating solution, developers may even consider large fixed-bottom jacket foundations for the substation in water depths up to 80-100m.

An alternative to a single offshore substation is a distributed transformer system, currently under development for fixed-bottom offshore wind, which would consist of several transformers distributed through the wind farm and located on the same foundation as the turbine at the end of each string of turbines. The Siemens OTM (Offshore Transmission Module) concept is expected to deliver a cost saving of up to 40% compared to conventional high voltage AC substations and could in theory also be applicable to floating offshore wind. The impact of the additional weight on the stability of the platform would need to be considered and may require modifications to the design of the platform of a number of concepts, but the potential for a net cost saving should be investigated.

The availability of high voltage dynamic cables is another important consideration for commercial-scale floating offshore wind projects. Early demonstrations have thus far used low voltage (33kV or 66kV) cables to export power back to shore. However, larger projects further from shore will require high voltage cables (132kV to 220kV) to minimise electrical losses. While 132-220kV cables are common in fixed-bottom projects, developing dynamic 132-220kV cables could present a major challenge for the industry, particularly in the absence of a market to drive the technology development. While a number of cable suppliers are expected to have the capability to develop appropriate dynamic cables, particularly given their extensive experience in the oil and gas industry, intervention may be required to incentivise cable qualification, as evident with the development of 66kV inter-array cables for the offshore wind market.[1]

This all assumes that AC transmission will be used. If wind farms move beyond ~100km from shore, DC transmission may be required, which will pose even greater challenges associated with the larger transformer platform size and larger dynamic cables required. It is expected that the majority of floating wind farms will be located in areas close to shore (<100km) to avoid the costs and risks associated with DC transmission.

Wake effects

Understanding wake effects has been a key focus area for fixed-bottom offshore wind, in order to reduce energy losses in an array. Software tools have been developed to help developers to maximise the yield of their wind farm through optimised array layouts. For fixed-bottom wind farms, the wake losses can be modelled and predicted to good levels of accuracy. However, for floating wind farms this may be challenging, particularly for concepts using slack catenary or semi-taut mooring configurations (semi-submersibles and spar-buoys), which will allow the structures to move laterally. Such concepts may move by up to 50 metres, meaning that fixing an array layout will not be impossible. The associated impact on wake effects is not currently well understood and could have implications for yield and turbulence-induced fatigue. Further research to understand the impact of wake effects on floating wind farms should therefore be a priority.

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[1] The Carbon Trust's Offshore Wind Accelerator programme awarded grant funding to three cable manufacturers to qualify four 66kV cables for the offshore wind market – see http://www.carbontrust.com/about-us/press/2014/07/carbon-trust-awards-funding-to-cut-offshore-wind-costs-by-up-to-100m-per-year

3.2 Fabrication & Supply Chain

Supply chain:

- Scotland have a number of existing suppliers which could service the floating wind industry, largely through leveraging existing capabilities and activities in the oil and gas, marine, and offshore renewables industries.
- No major supply chain bottlenecks are foreseen over the short term, but for commercial-scale deployments there are potential bottlenecks in bespoke installation vessels for certain concepts, floating substations/transformers, dynamic export cables, and suitable ports with large dry dock facilities.

Fabrication process & facilities:

- Fabrication of steel structures is analogous to shipbuilding, which will enable floating wind to leverage existing shipbuilding capability and facilities.
- Concrete structures typically use slip-form fabrication methods, which are again common in other industries, such as bridge building. Large set-down area is often needed, although some concrete structures can be fabricated on the installation barge, removing the need for extensive onshore fabrication facilities.
- Dry docks are preferable for assembly and load-out of the platform, as this can avoid the need for heavy-lift cranes.
- Semi-submersibles require a larger draft during load out and assembly than other concepts, which could constrain construction to fewer port facilities.
- Yard requirements for floating wind farm deployment is poorly understood by many designers, and should be considered earlier in the design phase to ensure that the full lifecycle costs are accounted for and minimised.
- Many concepts have adopted modular designs to unlock the benefits of serial fabrication.
- Fabrication time is longer for the larger and more complex semi-submersible structures. Simple, uniform spar-buoy concepts are well suited to rapid plate rolling methods, resulting in a quicker throughput time.

Port and fabrication facilities in Scotland:

- Scotland has a large number of ports and fabrication facilities suitable for floating wind farm construction, which are located in regional clusters near to offshore sites identified for floating wind development.
- Existing capabilities and facilities from the oil and gas industry can be leveraged and could provide competitive advantage for Scotland over other markets.
- The availability of sufficiently large dry docks is a potential bottleneck for the cost-effective large scale build-out of floating wind farms.

Supply chain

The sourcing of suppliers for any offshore wind project will be heavily dependent on the site location, but floating wind manufacturers appear confident that the European supply chain is suitably equipped to meet the needs of their projects. Many manufacturers expressed an eagerness to maximise local content, particularly those with concrete designs, but some did also admit that components could be sought from Asia at lower cost if European prices were not competitive. Within Europe, the UK is the most popular location to source suppliers for both the floating platform (figure 3.2.1) and the mooring and anchoring system (figure 3.2.2). Of these UK suppliers, around half are located in Scotland, with manufacturers highlighting on average 3-4 suppliers which could fabricate the floating platform and ~2 suppliers for the moorings and/or anchors. Leveraging the experience and capabilities of these suppliers, which have largely operated in the shipbuilding and oil and gas industries to date, could be critical to Scotland's efforts to take a leading role in the floating wind industry. Indeed, developers looking to build first array projects in Scotland – Statoil and Atkins/Pilot Offshore – have highlighted the strengths of the local supply chain as key reasons for selecting their respective site locations, both on the Scottish east coast.

Figure 3.2.1. Share by country of likely locations to source the floating platform

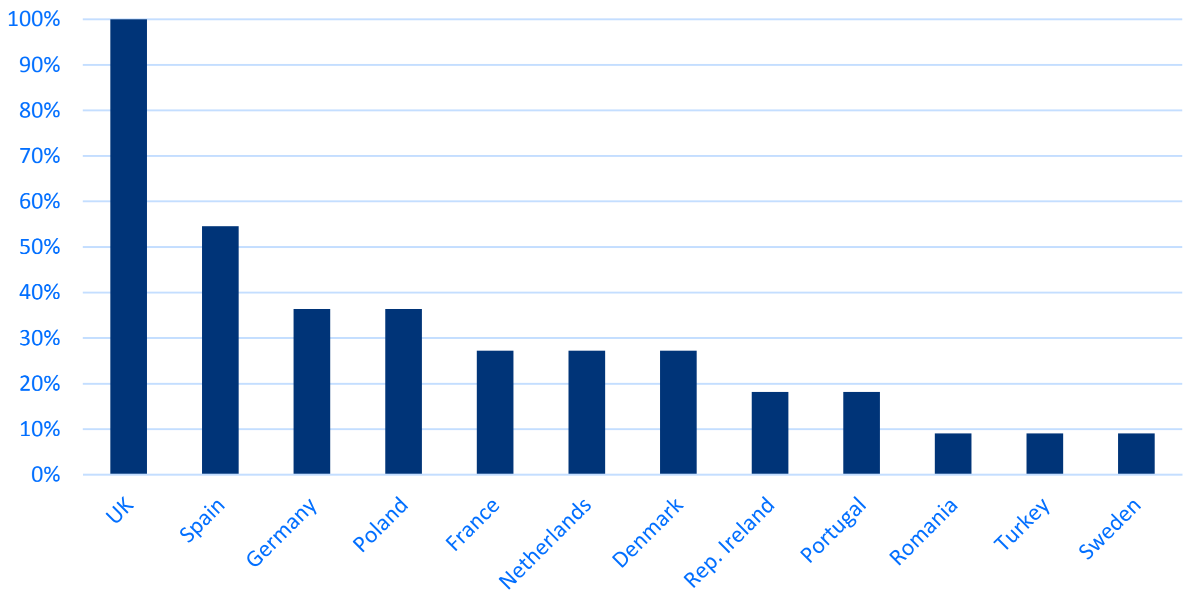
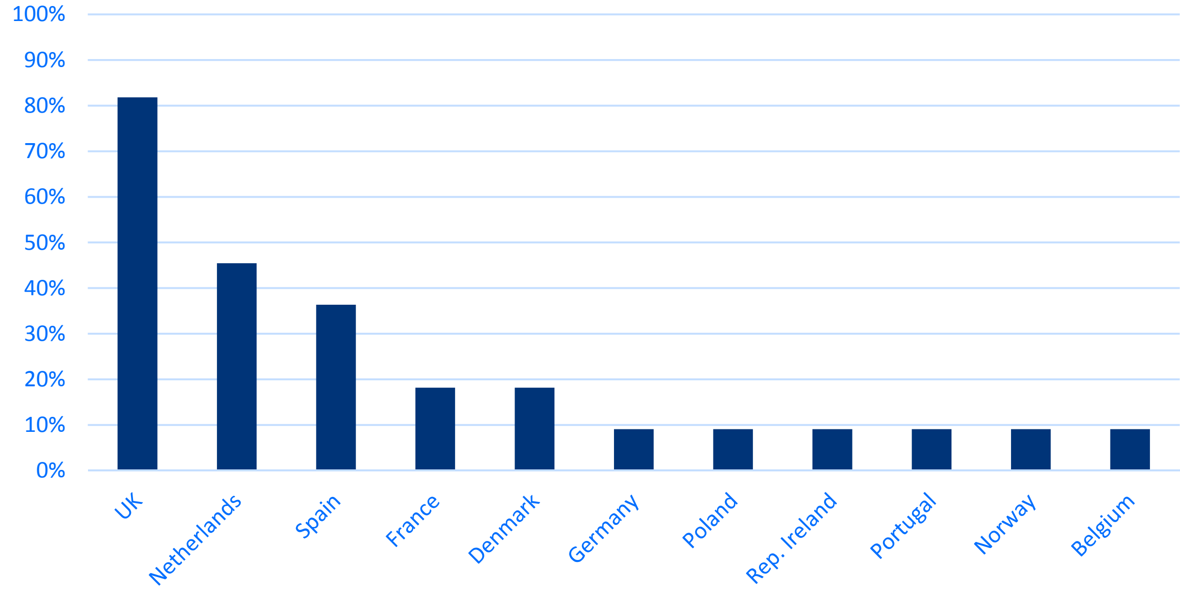


Figure 3.2.2. Share by country of likely locations to source the moorings and anchors



Supply chain bottlenecks

Importantly, no major short-term supply chain bottlenecks were flagged; however, as deployment ramps up to larger scales and commercial wind farms are developed, a number of potential bottlenecks exist.

Unlike fixed-bottom offshore wind farms, where heavy-lift crane vessels are required for installation, vessel availability for floating wind is not expected to be a major issue, since standard tug boats, barges and anchor handling tugs are generally readily available. However, concepts which require bespoke vessels may have difficulty in reaching sufficient volumes of scale to justify the investment cost, and may struggle to find suitable barges to retrofit in the nearer term. Likewise, spar concepts requiring dynamic positioning vessels for turbine installation may also experience bottlenecks, especially if competing with other offshore wind projects to hire such vessels.

Another likely bottleneck as floating wind moves to commercial scale is the availability of suitable dynamic cables, particularly for the high voltage export cable (220kV). Early demonstrations and pre-commercial arrays are able to use relatively low voltage dynamic cables (33kV / 66kV) to transmit the electricity back to shore, often over short distances. However, as sites are located further from shore and with larger power capacities, higher voltage cables will be required, likely at 220kV. Future RD&D efforts will need to design, test, and certify suitable dynamic cables for the floating wind market.

Similarly, floating substations (transformer platforms) will be required to step up the voltage for export back to shore. The world's first floating substation was installed off the coast of Fukushima, Japan, in 2013, but there are currently no installations in Europe. Reducing the size and weight of the transformer platform will critical to keeping costs down, and alternative bespoke floating platforms may need to be developed. Again, this could be tackled by future RD&D initiatives.

Fabrication process & facilities

Fabrication of floating wind structures is largely analogous to shipbuilding, which enables manufacturers to leverage existing shipbuilding facilities, but modified to align with the serial production needs of the offshore wind industry. Like with shipbuilding, the fabrication process will be yard dependent, so will be adapted according to the facilities available. In general, a large yard will be required with suitable equipment to enable serial fabrication of the platforms, with a batch plant set up locally at the shoreline staging area to facilitate rapid deployment following fabrication.

For steel structures, fabrication will consist of plate cutting, bending, rolling, welding, and coating. Steel fabrication will therefore require plate rolling and welding machinery suitable for serial production. Component assembly will take place first – for steel semi-submersible designs this could include the water entrapment plates, column shells, steel joints – before final assembly where the full structure will be welded together. Many concepts have adopted modular designs where the hull will be fabricated and assembled in sections. This can facilitate more effective serial fabrication processes and reduce the requirements for heavy lift cranes at port-side. Finally, a series of protective coatings will be applied to protect the steel against corrosion. Once assembled, the structure is either lifted into the water or skidded over a slipway into the water or a dry dock ready for turbine assembly.

Concrete platforms will be fabricated differently. Local suppliers of reinforced concrete will be required, and the platform will usually be constructed through a slip form process, where concrete is poured continuously to form a single continuous structure with no joints. The process will require a large set-down area and a quay with sufficient load bearing to cope with the weight of the structures. Some concrete structures will even be constructed on the installation barge, removing the need for extensive onshore fabrication facilities.

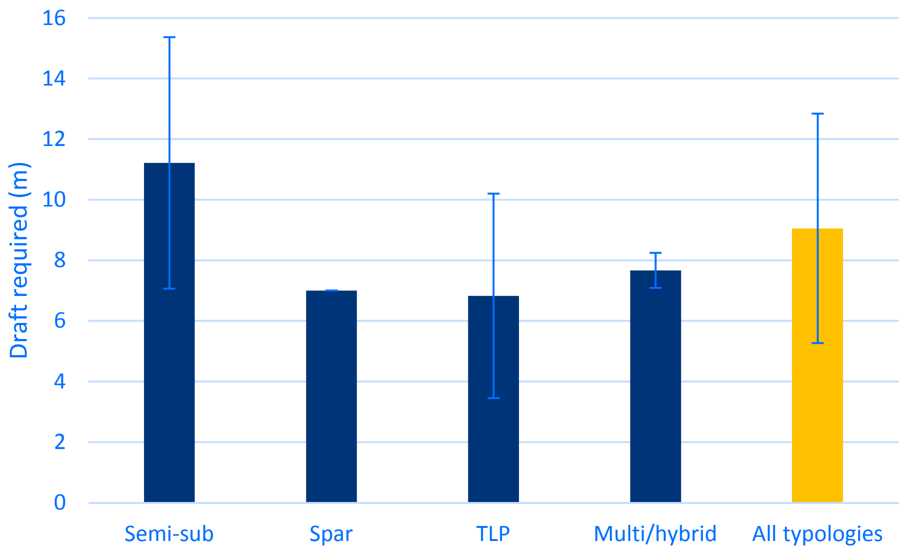
Standard yard facilities, such as cranes, are required for load out. While a dry dock is preferable for most concepts, a slipway is also suitable. Ideally, the use of heavy lift cranes will be limited, hence why a dry dock is usually desired. This means that the maximum crane capacity can be limited to ~200-300 tonnes, to undertake RNA (rotor nacelle assembly). Onshore lifting of the full structure can require cranes with a lifting capacity of up to 1500 tonnes, which are in short supply and consequently very expensive.

An additional consideration is the available draught and beam at port-side, to allow for assembly and transit to site. Another advantage of a dry dock is that it can be flooded to the optimal level for turbine assembly, before being floated out. There are a number of dry dock facilities available in Scotland, but these were originally constructed for long and slender naval vessels and most are not large enough to accommodate wide floating wind platforms, with the exception of two facilities, at Nigg and Kishorn. Dry dock availability is therefore a potential bottleneck for cost-effective large-scale build out of floating wind farms.

Draft during assembly/load-out

Most floating wind concepts require a draft of around 6 to 8 metres during load-out and turbine assembly (figure 3.2.3), which is within the capabilities of most port facilities identified in Scotland for floating wind projects. However, for semi-submersibles the required draft is significantly higher, at ~11 metres on average. It should be noted that some semi-submersible concepts were below the 9 metre depth available at most ports, but for those which exceed this level, the draft required could prove to be a major stumbling block for future development.

Figure 3.2.3. Quay-side water depth required for assembly/load-out



Yard size

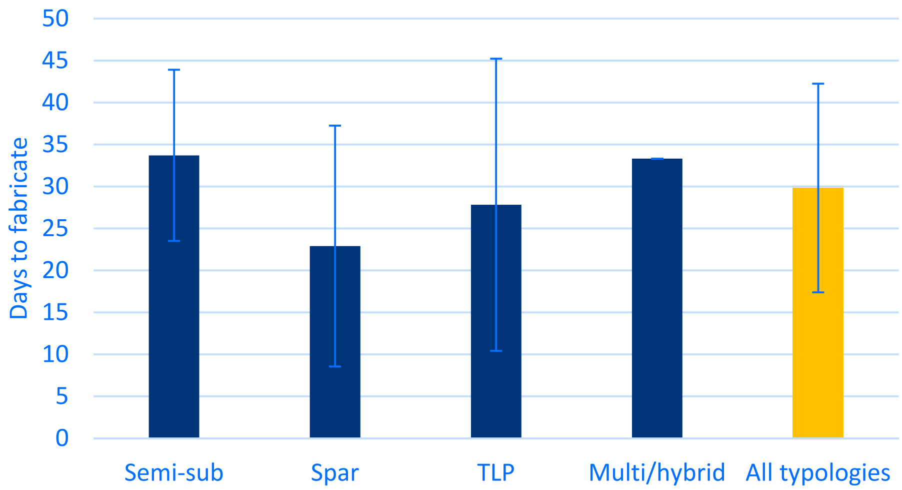
Floating wind designers were asked to provide details on the expected yard size is required to fabricate the structures. The large range of responses provided implies that this is an area that has not been considered in great detail by many designers. Despite an average response of ~100,000 m^2 (10 ha), some manufacturers consider a need for significantly larger yard sizes up to 400,000 m^2 (40 ha), while others expect to only require 5,000-10,000 m^2 (0.5-1 ha). In some cases this is justified, particularly for concepts which can be constructed directly on the installation barge, removing the need for significant onshore manufacturing facilities; however, this appears to be an area which designers and manufacturers need to understand in greater detail when considering the full requirements for deployment.

Fabrication time

Fabrication time also saw mixed responses, with large variance between different concepts. However, a few rough trends were evident. Namely, the time to fabricate a single structure can be reduced by ~80% from prototype to commercial scale, when serial fabrication can be conducted, from ~150 days to ~30 days. With multiple simultaneous operations, this results in a floating platform produced roughly every 7 days, on par with existing production rates for fixed-bottom offshore wind foundations.

There is also variance between typologies (figure 3.2.4). Fabrication time for spar-buoys is quicker than for other concepts, largely attributed to the ease of fabricating the simple uniform structures. Conversely, the more complex semi-submersible and multi/hybrid concepts take longer to fabricate, expected to be due to the number of components and welds required during assembly. TLP structures are also fairly complex designs to fabricate, but the smaller size supports more rapid manufacture. It should again be noted that there was a wide range of values from different designers, highlighting that this is an area which requires further investigation for many concepts.

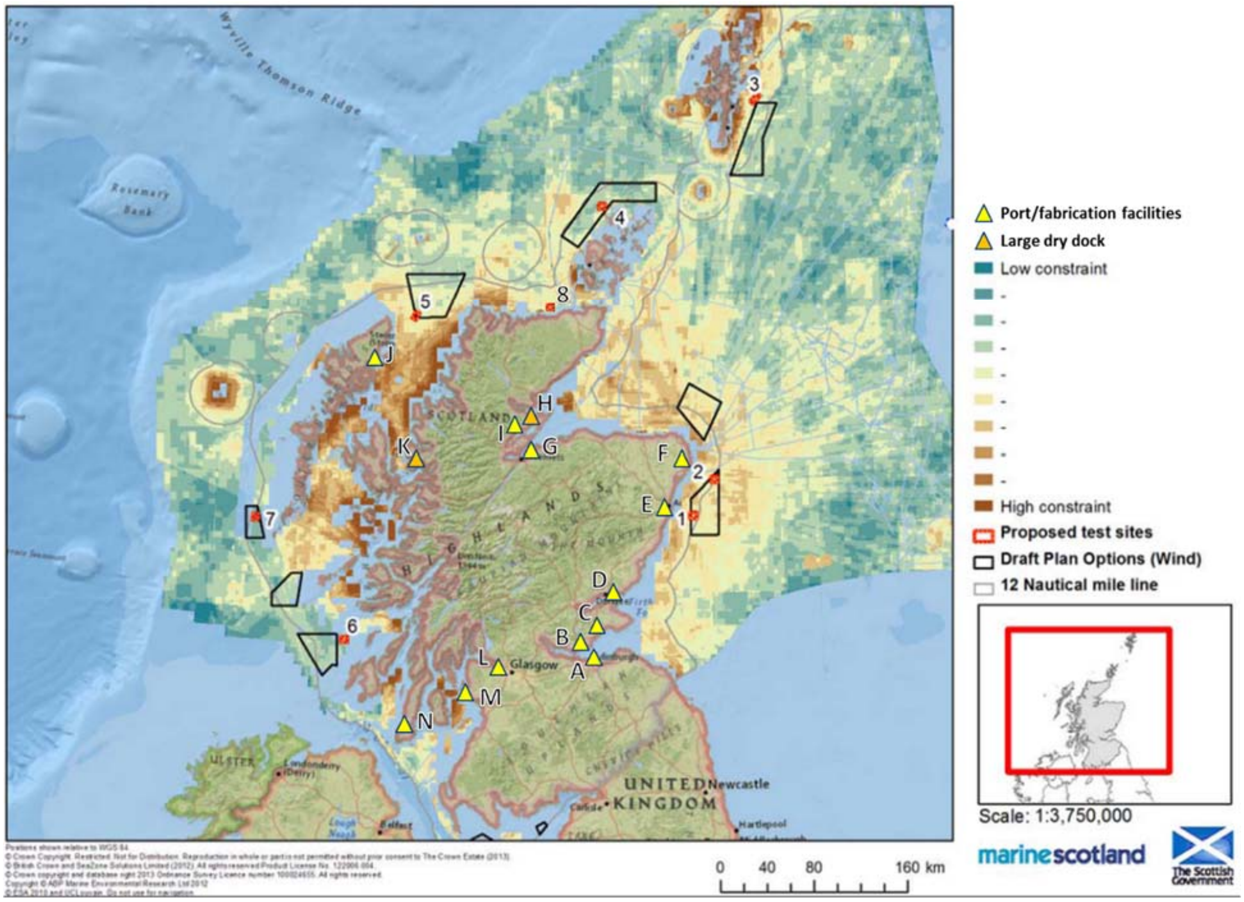
Figure 3.2.4. Fabrication time for a single platform in a commercial wind farm



Port and fabrication facilities in Scotland

Scotland has a number of suitable facilities for the fabrication and installation of floating wind turbines, where offshore renewables are able to leverage existing infrastructure and expertise from the North Sea oil and gas industry. 11 of the 14 facilities highlighted have been selected by Scottish Enterprise and Highlands & Islands Enterprise under the National Renewables Infrastructure Plan (N-RIP) as locations with the greatest potential to support the emerging offshore renewables industries (see * in list below). As can be seen in figure 3.2.5, the locations are generally well-positioned to service the most promising sites for floating wind development, as identified by Marine Scotland; namely, near-shore deep water locations which are exposed to mean annual wind speeds exceeding 9 m/s. However, their availability for floating wind projects will likely be influenced by level of oil and gas activity in the North Sea, which could drive up costs if there is increased demand.

Figure 3.2.5. Location of port and fabrication facilities in Scotland capable of servicing the floating wind industry (adapted from Marine Scotland, 2014)



- A: Port of Leith*
- B: Rosyth Dockyard
- C: Methil (BiFab)*
- D: Port of Dundee*
- E: Aberdeen Harbour*
- F: Peterhead Port*
- G: Port of Ardesier*
- H: Nigg (Global Energy Group)*
- I: Invergordon (Global Energy Group)
- J: Arnish (BiFab)*
- K: Kishorn Port*
- L: Inchgreen Dry Dock
- M: Hunterston Terminal*
- N: Machrihanish/Campbeltown*

Other facilities in the UK:

- Harland & Wolff, Belfast, Northern Ireland (north-east)
- Barrow Shipyard, England (north-west)
- Cammell Laird, England (north-west)
- ABLE Marine Energy Park, Humber, England (east)
- A&P Group, Tyne yard, England (north-east)
- A&P Group, Tees yard, England (north-east)
- A&P Group, Falmouth, England (south-west)
- Milford Haven, Wales (south-west)
- Port Talbot, Wales (south)

The facilities adhere to the formation of local clusters of port, fabrication, and supply chain services that can present a strong offering to prospective developers. While facilities in the Edinburgh cluster (A to D) are more likely to service fixed-bottom offshore wind sites in the Firth of Forth (e.g. Neart Na Gaoithe Wind Farm), facilities at Aberdeen and Peterhead are well-placed for floating wind development off the east coast (e.g. Hywind Pilot Park, Kincardine Offshore Windfarm). Other clusters, such as those around Inverness (G to I), the Western Isles (J and K), and Glasgow (L to N), are slightly further away from designated development sites, but are still well-placed to service floating wind projects to the north, north-west, west, and even the east of Scotland. For example, the Kincardine project intends to use Global Energy Group's advanced fabrication facility at Nigg to construct the WindFloat structures, which will be towed 100 nautical miles to site. Near-to-site Nigg Bay, outside of Aberdeen Harbour, will be used as an O&M port. The clusters identified around Scotland can enable developers to tap into the wealth of offshore engineering expertise that already exists in the region and benefit from high quality port and fabrication facilities.

However, a number of the facilities identified will likely need upgrades to the existing infrastructure to adapt to floating wind construction, by upgrading quaysides (e.g. expanding dry docks), increasing water depth (e.g. >9 m), improving port access (e.g. entry width), and upgrading onshore facilities (e.g. craneage). As can be seen in table 3.2.1, quay-side depth ranges from 4.5 to 14 metres, though most facilities have up to 9 metres of water depth. While this is suitable for spar and TLP concepts (not spar erection), for some semi-submersible concepts this could pose problems (see figure 3.2.3).

Another important consideration is the width of the port entrance. Most port facilities have been designed to accommodate long and slender naval vessels; however, floating wind platforms are often very wide structures, with beam reaching up to 100 metres in some concepts. This may again cause a disadvantage for semi-submersibles as opposed to the more slender spar-buoy and smaller TLP concepts. Dry dock facilities suitable for floating wind platforms are therefore limited to those with a 'large' dry dock where the width exceeds 80-100 metres. There are only two dry docks in Scotland with sufficiently large beam to support all types of floating wind concept – Kishorn, which is able to service the west coast, and Nigg, which is able to service the east coast (indicated by amber triangles in figure 3.2.5). Both are able to supply project to the north of Scotland. However, the long distance to tow the structures to site is not optimal, and a shortage of dry docks could cause bottlenecks if floating wind reaches large scale deployment.

Table 3.2.1. Port characteristics and specifications

Facility	Dry dock size (length x beam)	Quay-side water depth	Onshore area	Quay-side length
Leith	Medium (168m x 21m)	7.1 m – 9.1 m	150 ha	1800 m
Rosyth	Large (320m x 42m)	12.5 – 13.7 m	6 ha	500 m
Methil	-	9.0 m	14 ha	240 m
Dundee	Small	7.1 m – 9.1 m	60 ha	1800 m
Aberdeen	Medium (112m x 21m)	9.6 m – 13.3 m	10 ha	520 m
Peterhead	Medium (58m x 11m)	7 – 14 m	8 ha	2100 m
Ardersier	-	4.5 – 8.0 m (proposed upgrade to 9.5 m)	270 ha	1000 m
Nigg	Large (300m x 150m)	4.5 – 9.5 m	96 ha	725 m
Arnish	-	6.5 m (proposed upgrade to 8.5-9 m)		100 m
Kishorn	Large (160m beam)	8 – 13 m	45 ha	120 m
Inchgreen dry dock	Large (305m x 44m)	7 – 12 m	12.5 ha	390m
Hunterston	-	4.2 m (proposed upgrade to 9 m)	37 ha	67 m (proposed upgrade to 300 m)
Campbeltown	-	9 m	409 ha	

N.B. Dry dock size defined by www.ports.com. 'Large' dry docks with a beam exceeding 80 metres are suitable for all floating wind concepts. 'Large' with a beam <80m and 'Medium' dry docks are only be suitable for spar-buoys.

Fabrication challenges

The main challenges for fabrication are shown in table 3.2.2 below. Manufacturing is not considered to be a major issue in itself, since the manufacturing techniques are well known from other industries. However, some designers highlighted the need to build more experience in welding large diameter steel columns in order to maintain a consistent geometrical shape of steel structures and limit butt weld misalignments. For concrete designs, ensuring high quality slip-forming is highlighted, in order to avoid concrete joints. There is also a need to refine serial fabrication processes, factoring this into the floater design – possibly through more modular designs – and optimising the manufacturing process to reduce throughput time of both the platform and the turbine.

The main challenges are perceived in the availability of suitable port infrastructure for the assembly and load-out of the structure. Although dry dock facilities are available in Scotland and other parts of the UK, many cannot support the wide beam of floating platforms and water depth required for turbine assembly. Existing facilities are expected to be suitable for early demonstrations and pre-commercial arrays, but commercial scale build-out of floating wind may require investment to upgrade port infrastructure.

The load out process for floating wind platforms can vary significantly between different facilities. In the absence of suitable dry docks, platforms will need to adapt their designs to support easier and more cost-effective load-out. Following load-out of the platform, RNA assembly can create challenges for facilities, largely due to the high hub height and large weight of the nacelle. Large port-side cranes will be required, though this is not considered to be an overly significant bottleneck.

Table 3.2.2. Key fabrication challenges

Challenge	Mitigation
Steel: Maintain geometrical shape of steel structures and limit butt weld misalignments	Build experience in welding large diameter steel columns
Concrete: Ensure correct, continuous concreting, thereby avoiding concrete joints	Facility working 24/7 with the use of slipforms and very high quality control
Serial fabrication	Advanced design focused to simplify the manufacturing process
Reduce man-hours during fabrication	Efficient, well-coordinated design with the yard and the supplier
Logistics	Parallel serial fabrication of floater and wind turbine
Shipyards with sufficient dock size (dry dock with sufficient beam and water depth)	Extend dry dock capacity
	Use of submersible barge can replace dry-dock
Launching of the floater – load out can be highly variable depending on facility used	Adapt floater design to make load-out easier
RNA assembly (high hub height and large weight)	Large port-side cranes

3.3 Installation

Installation process:

- Major benefit of floating wind is the ability to conduct more onshore/port-side operations than possible with fixed-bottom wind farms.
- Semi-submersibles and TLPs are able to assemble the turbine at port, removing the need to charter expensive heavy lift vessels.
- Spar-buoys must be transported to a sheltered deep water location for erection and turbine assembly, using heavy-lift vessels.

Vessel requirements:

- Semi-submersibles have the lowest vessel constraints, requiring only simple tug boats to tow the fully-assembled structure to site for hook-up, in addition to the obligatory anchor handling tugs and cable lay vessels.
- TLPs are slightly more constrained, often requiring a bespoke barge for optimal installation procedures; although standard barges can be used in the intermediary.
- Spar-buoys have the greatest vessel requirements, often needing a barge to float the structure to a deep water location (wet-tow also possible) and a heavy-lift vessel for turbine assembly.

Draft requirements:

- Larger and heavier semi-submersible platforms typically require a larger draft at port for turbine assembly and during transit, but can be installed in shallower water depths.
- Assembly and transit to site for TLPs and spars will typically take place on a barge which can operate in a relatively shallow draft.
- Spar concepts require a large draft in excess of 80-100m for erection and turbine assembly, as well as a deep water route to site for final hook-up, which could constrain their application to fewer sites.

Met-ocean limitations:

- Offshore turbine assembly creates tighter weather constraints for the installation of spar-buoy concepts. However, once assembled, the stability of the ballasted structure facilitates transit to site in larger wave heights.
- Transit to site in challenging conditions is also possible for TLPs, supported by the seafaring capabilities of the installation barge. However, the complex installation process and lack of buoyancy stability without mooring tension limits the installation of TLPs to ~1.5m Hs.
- Semi-submersibles are the most flexible, with installation possible in wave heights up to ~2m.

Installation time:

- Complex and weather-constrained installation procedure for TLPs results in a significantly slower installation process than other concepts, with up to ~40 hours required even during commercial application.
- Installation time for semi-submersible and spar concepts is shorter, at ~20-24 hours.

Installation cost:

- Net effect of the factors above is more expensive installation for spar-buoys, largely driven by the greater vessel requirements and met-ocean limitations during turbine assembly.
- Installation costs are also high for TLPs due to the met-ocean limitations and extended installation time.
- The simplicity and flexibility of semi-submersibles results in a lower installation cost.

Installation process

A brief overview of the installation process for floating wind structures is detailed below:

1. Load-out of the platform from port is conducted by either flooding the dry-dock, or using a slipway or heavy lift vessel to place the structure in the water
2. Turbine is assembled on the platform port-side using onshore cranes (not applicable for spar-buoys)
3. Anchors and moorings are pre-installed using an anchor handling tug (AHT) and a remotely operated underwater vehicle (ROV). Moorings are proof loaded to 100% to verify structural integrity.
4. Electrical cables are pre-installed using a cable lay vessel
5. Structure is towed to site using simple tugs or on a barge
    a. Spar-buoys will be towed to a sheltered location for ballasting and turbine assembly, using a crane vessel, before final transit to site
6. Fully assembled structure is hooked up to the mooring lines and electrical cables
7. Ballast is added to stabilise the platform
8. Mooring lines are tensioned appropriately
9. Final commissioning

This process may alter for different concepts, depending on the platform design, strategies adopted, and the availability of suitable vessels and port infrastructure.

Onshore vs. offshore assembly

A major advantage of floating wind turbines over conventional fixed-bottom structures is the reduced number of offshore operations, which are constrained by weather windows and require expensive installation vessels. Most concepts will therefore try to maximise the number of operations that can be conducted onshore or port-side. The majority of concepts are able to assemble the turbine at port (figure 3.3.1). Moorings, anchors, and electrical cables are still typically assembled offshore, though some concepts are able to maximise port-side preparation, leaving only final hook-up offshore.

Spar-buoys are less amenable to port-side assembly (figure 3.3.2) due to the large water depths required to erected the structure, but assembly can still be carried out in a sheltered area near to shore, before being towed to site, which is less constrained by weather windows than turbine assembly for fixed-bottom installations. TLP concepts generally tend to undertake more operations port-side, largely due to the need to ensure that mooring legs are appropriately tensioned with balanced load distribution. Modifying loads after the legs have been tensioned could de-stabilise the structure. TLP concepts using gravity anchors (such as the Eco TLP and Blue H TLP) are able to limit offshore assembly to just the electrical cables, with the full mooring and anchoring system hooked up port-side prior to transporting offshore for installation.

Figure 3.3.1. Port-side vs. offshore assembly of floating wind components

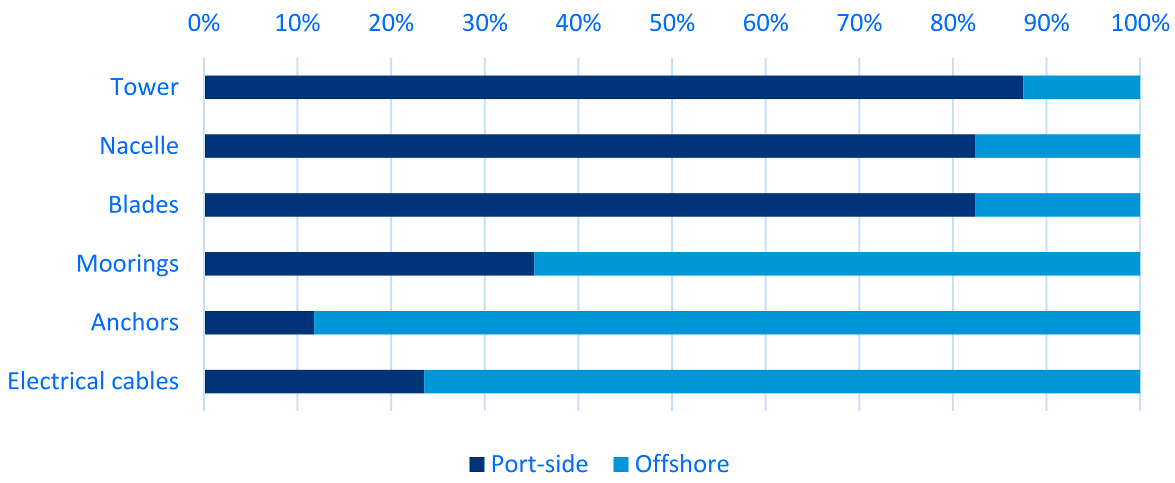
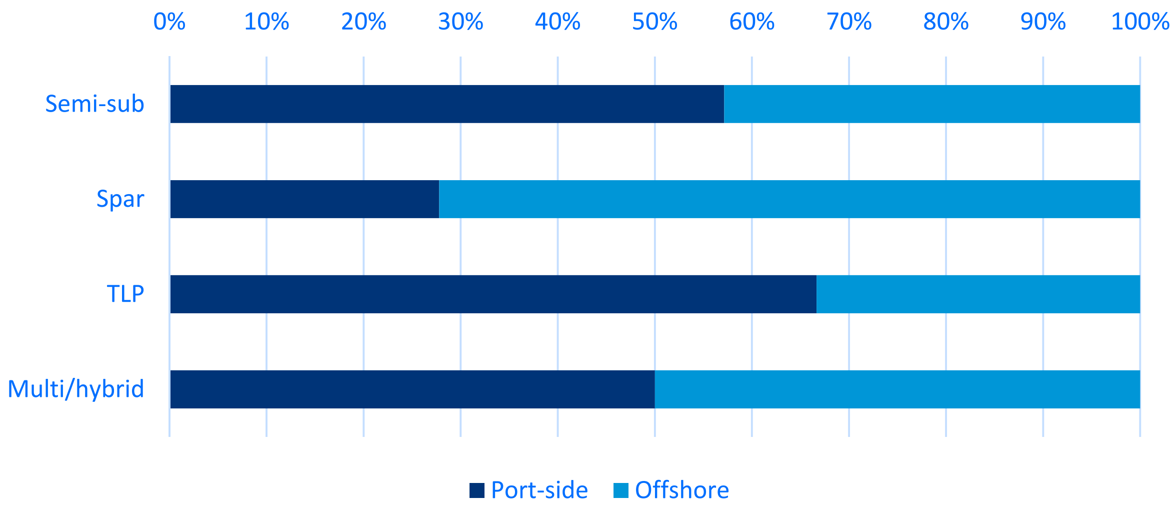


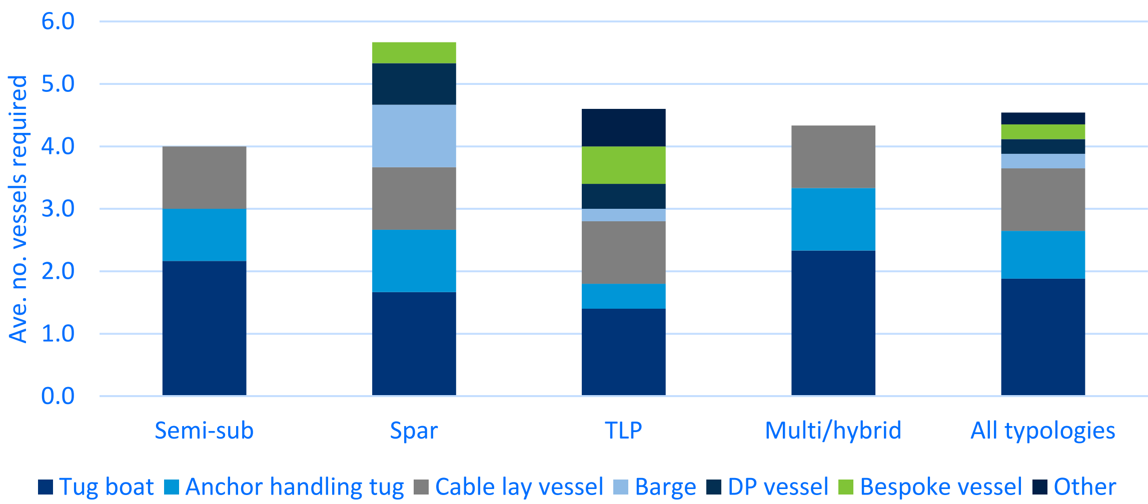
Figure 3.3.2. Port-side vs. offshore assembly by typology



Vessel requirements

The foremost benefit from limiting the number of offshore operations is removing the need for large jack-up and dynamic positioning installation vessels, which can cost ~£150,000 per day compared with the tug boats required for floating structures, which are ~80% cheaper at ~£30,000 per day. While tugs and cable lay vessels are common across all typologies, there is variation with regard to additional auxiliary vessels required (figure 3.3.3). Semi-submersibles have the lowest requirements, with just 4 basic vessels required on average. The additional offshore operations of spar buoys brings need for heavy-lift dynamic positioning vessels to conduct turbine assembly, as well as barges to transport the structure to a sheltered area to be erected, although a wet-tow is also possible. TLPs also require barges to transport the structure to site. For many, bespoke installation barges have been designed for the concepts, which become economical at a given scale of deployment. Prior to this, conventional barges may be used, but to deliver lower cost these concepts will need to achieve the levels of scale necessary to justify the additional investment in specialised vessels.

Figure 3.3.3. Vessel requirement during installation for floating wind structures

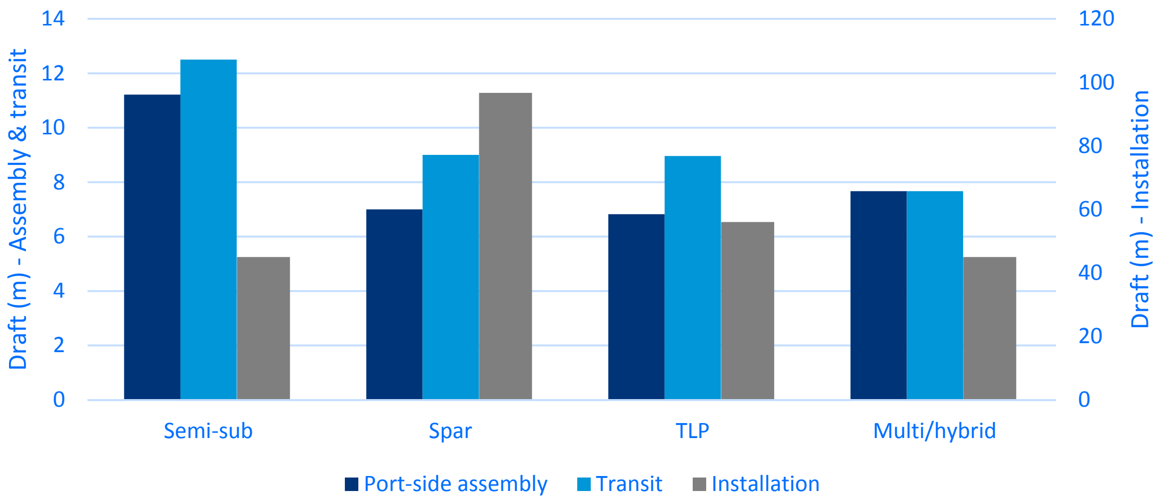


Draft requirements

Different concepts also impose different draft requirements during assembly, transit to site, and installation. Semi-submersibles require more depth at port and during transit due to the heavier mass of the full structure which is being floated and towed to site, whereas spars and TLPs will typically use barges for transit, which can operate in lower drafts (figure 3.3.4). This could have implications for concept selection if a small draft is required to comply with existing port facilities, particularly semi-submersibles, whose average draft exceeds the capabilities of most ports in Scotland (see section 3.2). If necessary, additional buoyancy aids may be required to reduce the required draft.

During installation, it is unsurprising that spars require significantly more draft to upend and install the structure. TLPs also require at least 50m draft to for installation, whereas semi-submersibles are more flexible and can be installed in slightly shallower water depths (from ~35m); although the optimal depth for both concepts is closer to 100m.

Figure 3.3.4. Draft requirements during assembly, transit, and installation

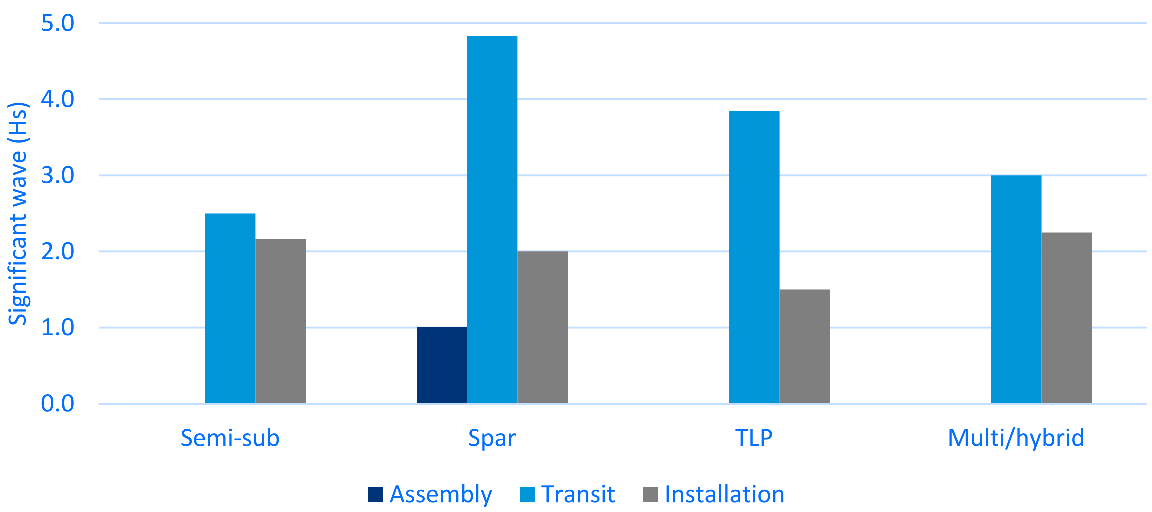


N.B. Transit depth for spars refers to transit prior to upending and turbine assembly. Once assembled, spars will require water depth in line with the installation draft in order to tow the structure to site for hook-up and commissioning.

Met-ocean limitations

Met-ocean limitations are important for reducing weather downtime during the installation process. Being able to operate in greater wave heights can help to minimise the installation time and reduce the cost of installation. Met-ocean conditions during assembly are only relevant to spar buoys, which can be constrained to just 1m wave height; hence why a sheltered deep water location is required close to port. However, once the spar has been upended, its stability allows for transit in difficult ocean conditions. Identifying suitable sheltered areas could be a constraint to the application of spar buoys given the deep waters required.

Figure 3.3.5. Met-ocean limitations during assembly, transit, and installation



For TLPs, transit is claimed to be possible in up to ~4m wave height, since most TLP concepts will be transported on a barge. However, the more complex installation process requires <1.5m wave height, which can reduce the available weather window for installation despite the high proportion of operations conducted at port. Semi-submersibles are the most flexible with regards to installation, not constrained by water depth and more tolerant of harsh marine conditions for installation.

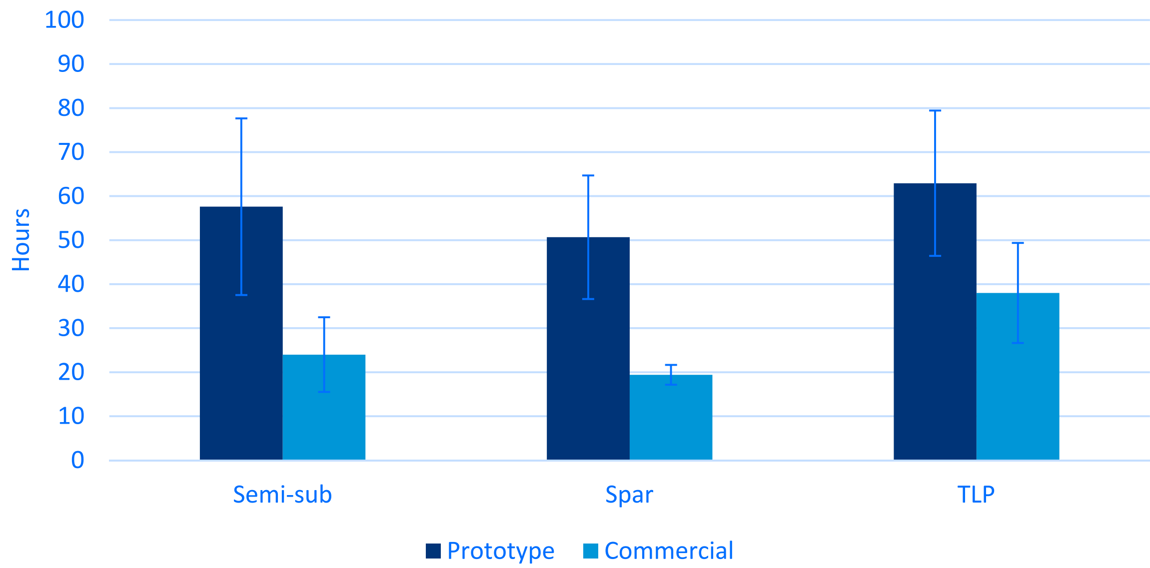
Installation time

The number of offshore operations, level of met-ocean limitations, and complexity of the installation process will all impact on installation time, which is a key driver of costs. Significant time reductions are expected between prototype and commercial stages of deployment, roughly halving the time to install the devices as procedures are optimised (figure 3.3.6). Although the more mature concepts which have conducted full-scale installations report longer installation times at the prototype stage.

The more challenging installation process associated with TLP concepts results in a longer installation time, which is also more susceptible to harsh weather conditions. Indeed, the longer installation time for TLPs is even more pronounced when only considering the more mature concepts, implying that this is an area underestimated by early stage designers and which requires much attention.

For semi-submersible and spar-buoy concepts the installation time is similar, which is surprising given the additional offshore operations required with spar-buoys. Nevertheless, while the added offshore operations for spars will increase the time required, the greater resilience to difficult met-ocean conditions once the structure has been upended can increase the weather window available. Securing an easily accessible sheltered area close to port is key to unlocking this.

Figure 3.3.6. Installation time for prototype and commercial deployments



N.B. Data on multi/hybrid concepts was not of sufficient quality to be included in the analysis.

Installation Summary

Semi-submersibles represent the most flexible option with regard to installation, performing well on most metrics (table 3.3.1). Spar-buoys are heavily constrained by the operational draft required, which precludes turbine assembly at port and creates a need for more expensive dynamic positioning vessels and cranes. TLPs are able to conduct most operations at port, but the complexity of the installation process, largely attributed to the lack of buoyancy stability in the platform without mooring tension, makes them more susceptible to harsh met-ocean conditions and increases the installation time.

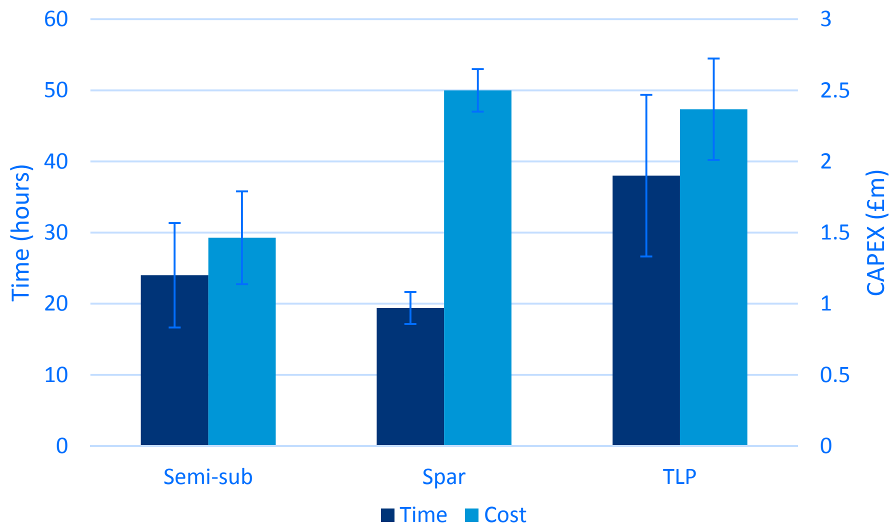
Table 3.3.1. Summary of installation strengths & weaknesses by typology

Typology	Assembly (port vs offshore)	Vessel requirements	Draft requirements	Met-ocean limitations	Time to install
Semi-sub	3	3	3	2	3
Spar	1	1	1	2	2
TLP	2	2	2	1	1
Multi/hybrid	2	3	2	2	-

Installation cost

Of the metrics listed above, the two most important drivers of installation cost are time and vessels. The long installation time for TLP concepts drives up costs compared to semi-submersible platforms, despite both concepts using low cost vessels (figure 3.3.7). Optimising the installation process should therefore be a critical area of focus for TLP designers. Conversely, for spar-buoys, installation costs are considerably higher than the other typologies due to the added expense of hiring heavy lift crane vessels for turbine assembly. Installation costs are seen to be underestimated by all of the more nascent concepts, with higher costs envisaged by designers of the more mature concepts, particularly with TLPs.

Figure 3.3.7. Installation time vs. cost



Installation challenges

The main challenges for the installation of floating wind devices are shown in table 3.3.2. Installation time and vessel costs are the key focus of efforts to reduce overall installation costs. Integrating installation procedures into the design phase early on can help to develop optimised solutions, and better weather monitoring together with the availability of vessels with lower met-ocean limitations can help to reduce weather downtime. Although developing bespoke installation barges will require sufficient volume to warrant the investment.

The installation of the moorings, anchors, and electrical cables is critical area which needs further optimisation. Equipment such as ROVs can help, but further research is needed in this area to improve the installation procedures to reduce the time and risks associated with the installation of these key components. Although the technology has been adopted from proven concepts in the oil and gas industry, tailored solutions are required for floating wind devices which are fit for purpose. This includes developing anchors challenging seabed conditions and developing low-cost methods for anchor testing and embedment.

Mating of the turbine onto the floating platform has also been highlighted as a challenge. Improved mating systems should be developed, together with closer cooperation between platform designers and turbine manufacturers.

The above challenges are relevant to all floating wind typologies, but a number of bespoke challenges have also been identified for spars and TLPs. For spars, maintaining roll stability when being towed to assembly site is an issue, though this can likely be mitigated through appropriate distribution of the ballast. Likewise, bending moments in the tower during upending can be mitigated through high quality steel materials. However, improving the attachment of the barge or tug boat to the upended structure during transit to site is expected to require new solutions.

Installation is arguably the single biggest challenge for TLP concepts. Maintaining stability to control the horizontal positioning of the structure during installation is particularly difficult. Further research is needed to optimise the entire operation and develop detailed method statements for the installation procedure, and active ballast systems may be required. Installation of the tendon legs and anchors also requires considerable attention, through further R&D and adopting learnings from qualification test rigs. In combination, overcoming these challenges could help to reduce the overall installation time for TLP concepts, which is currently at close to 48 hours, resulting in significant cost savings.

Table 3.3.2. Key installation challenges

Challenge	Mitigation
Installation time and vessel cost	Consider installation constraints during the platform design phase to optimise the installation process.
Weather restrictions imposed by tug boat and barge limitations	Good weather monitoring and installation planning
	Bespoke installation vessels (large-scale deployment)
Deepwater mooring and electrical cable installation	Optimise installation process
	Increased availability of deep water robotic vehicles (ROVs)
Challenging seabed conditions	Develop appropriate anchors for challenging seabed conditions
Testing and embedment of anchor requires either a high bollard pull tug (~250 t) or an external tensioning device	Large tug with bollard pull or use a stevtensioner during the mooring installation phase
Mating turbine onto structure	Improved mating systems
Attachment between the tug/barge and the structure when towing to site	New solutions
Spar: Roll stability during horizontal tow	Appropriate distribution of the ballast
TLP: Controlling the platform horizontal position during the entire installation process	Detailed method statements and procedures for entire operation
	Adopt active ballast systems to improve stability during installation
TLP: Allowable sea-state for installation (48 hour weather window for installation)	Installation barge enhancements (either retrofit or using bespoke installation barge)
TLP: Lowering anchors (gravity anchor)	Apply lessons learned from qualification test rig
TLP: Tensioning and grip-locking tethers	Constant weather monitoring and good planning

3.4 Operations & Maintenance (O&M)

O&M Strategies:

- O&M strategy for minor repairs similar to fixed-bottom wind farms, adopting the same methods of turbine access by crew transfer vessel.
- O&M strategy for major repairs likely to differ. Many floating wind concepts allow the option to tow the full-structure back to port for quay-side maintenance, avoiding the need to charter expensive heavy lift vessels; though the methodology of doing so has yet to be fully established.
- Cost benefit between tow-to-shore port-side repairs and conventional offshore repairs will be dependent on the distance from shore and susceptibility to met-ocean conditions. This, again, has not yet been fully investigated.
- Semi-submersibles are expected to be more tolerant to harsh conditions, with simple unhook, tow-to-shore, and reverse process for re-installation.
- For TLPs, the process will be more challenging and more prone to weather downtime.
- Spar-buoys will need heavy-lift vessels regardless, but may still benefit from transporting the structure to sheltered areas to limit weather downtime and additional daily charges for the heavy-lift vessel.
- Further research is needed to understand the method of undertaking major repairs, particularly in larger arrays without compromising the availability of other turbines, and will need to be benchmarked against conventional O&M strategies used in fixed-bottom wind farms.

Lifetime asset integrity:

- Primary components (platform, moorings, and anchors) indicate lifetime asset integrity of at least 20 years, with many beyond this.
- Concrete structures appears to have more longevity than steel structures.
- Experience from floating oil & gas platforms suggests that many structures exceed their design life, which could open opportunities for repowering.

Condition monitoring:

- Condition monitoring systems are employed on the platforms and moorings of most concepts.
- Given the nascent state of floating technology, these systems will likely need to be refined over time as more operational data is made available.
- Visual inspections are carried out on the platform and moorings every 5 years on average.

Sources of failure:

- Most likely sources of failure expected from fatigue and corrosion.
- Manufacturing defects and offshore collisions also considered a potential risk.
- Electrical cables, moorings, and anchors may be vulnerable to fishing activities.

O&M strategies for floating wind

Operations & maintenance for floating wind turbines is largely the same as for fixed-bottom offshore wind turbines. Minor repairs will typically be conducted by accessing the platform by crew transfer vessels, with technicians accessing the turbine to conduct repairs. Most floating concepts have designated boat landings on the floater to enable crew transfer and, despite the floating nature of the platforms, the weight and stability of the platforms are expected to allow conventional vessel thrusting and fender friction methods. Some concepts also enable transfer by air, with helidecks located on either the platform or the nacelle.

However, for major repairs, such as gearbox replacement, a different strategy is expected to be adopted. Whereas fixed-bottom offshore wind turbines require the use of large heavy lift vessels, at extremely expensive day rates and high mobilisation costs, many floating wind concepts are designed such that they can be towed back to shore for port-side repairs, using considerably cheaper standard tug boats and barges. The distance of the site from shore will be critical to the cost benefit of this strategy, but for sites less than 80-100km from shore, this could deliver competitive advantage for floating wind solutions.

The cost benefit will also differ between concepts, largely due to the met-ocean limitations and conditions in which the structures can be towed back to shore and then back to site. For semi-submersibles, which have greater tolerance to harsh conditions, it is likely that weather restrictions and downtime can be minimised and standard tug boats can be source quickly at low mobilisation costs. However, for TLP concepts, which are more sensitive to met-ocean conditions and may require a bespoke barge, the cost is likely to be higher.

For spar concepts, the full structure will not be able to be towed back to port, but to a sheltered deep water area. Given that a heavy lift dynamic positioning vessels will be required anyway, spars could adopt the same repair procedure as conventional fixed-bottom structures. However, given the ability of spar-buoys to be towed in an upright position in challenging weather conditions, there may be a cost benefit in unhooking and transporting the vessel to reduce the amount of weather days and therefore the number of days for which the vessel must be chartered, as well as the associated downtime.

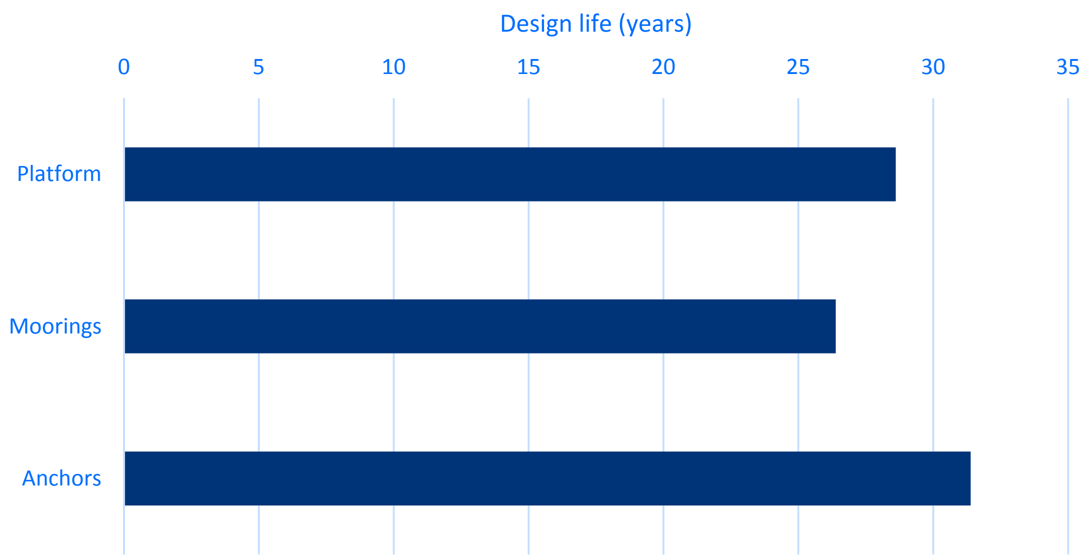
The alternative approach for major repairs remains theory only and has not yet been put into practice. Understanding the technical feasibility and cost benefit of this approach should be a priority, as well as identifying opportunities to optimise the process of disconnecting and reconnecting the device. Given the role of turbine manufacturers in undertaking O&M activities, there is a pressing need for further engagement with OEMs, both to mitigate risk and ensure that floating concepts are designed appropriately.

Lifetime asset integrity

Floating wind concepts show good lifetime asset integrity, with the platform, moorings, and anchors all designed within the minimum expected lifetime of 20 years. Many platforms (both steel and concrete) are also expected to be able to exceed this, which could unlock opportunities for repowering if structural integrity is proven in offshore conditions. Indeed, a number of floating platforms in the oil and gas industry have exceeded their design life specifications.

The asset integrity of moorings and anchors is also vital to avoid the expensive and disruptive replacement of mooring lines. While this has been flagged as a potential issue in Japan, where mooring line replacement is expected after 10-15 years of operation, in Europe designers are confident that moorings are capable of lasting the full project lifetime. Again, experience from the oil and gas industry suggests that this will not be a major issue for floating wind, provided regular inspection and maintenance is undertaken.

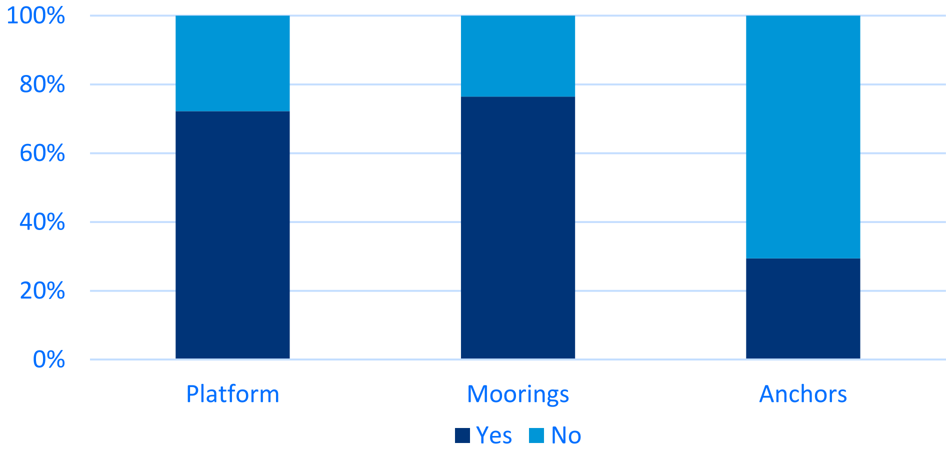
Figure 3.4.1. Lifetime asset integrity of floating wind concepts



Condition monitoring

Each component is expected to last the full project lifetime without major repairs, but platform inspections will be carried out every 1-5 years, with inspections of the moorings and anchors every 5 years. Condition monitoring systems will also be used on most devices, particularly on the platform and moorings, which will limit the need to go offshore to conduct inspections (figure 3.4.3).

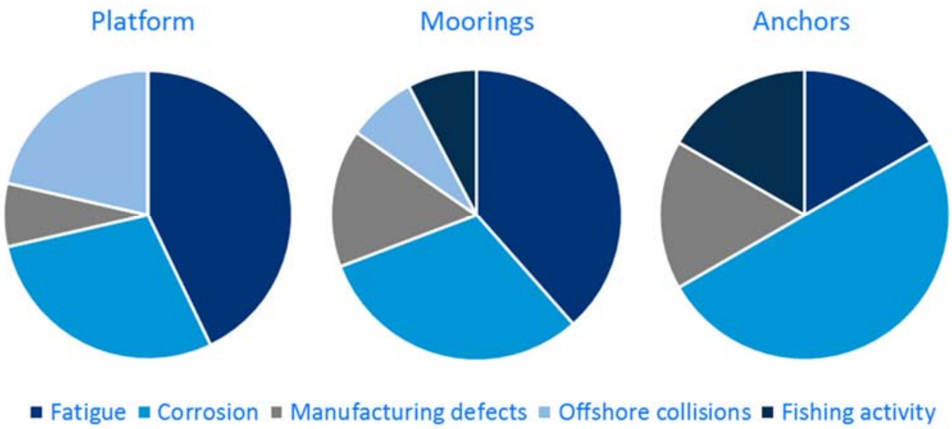
Figure 3.4.2. Share of concepts using condition monitoring systems



Sources of failure

Expected sources of structural failure across the main components are mostly attributed to corrosion and fatigue (figure 3.4.4). Platforms could also be susceptible to offshore collisions with vessels, as well as manufacturing defects, such as the quality of steel/concrete and the quality of the welding and coatings. Manufacturing defects are also highlighted in the moorings, related to casting imperfections in the mooring chains, as well as kinks of entanglement during the installation process. And fishing activity is a risk, with fishing lines and trawlers capable of getting caught on mooring lines. For TLPs, fatigue in the tendon fibres is a risk, although most concepts will have built in redundancy through additional tendons, should any fail. Anchors are at lower risk of failure, with corrosion the most likely source of problems.

Figure 3.4.3. Most likely sources of failure in floating wind systems (excl. turbine)



O&M challenges

The main challenges for the installation of floating wind devices are shown in table 3.4.1. The O&M challenges identified are largely the same as for fixed-bottom offshore wind farms; namely improving turbine accessibility and reducing the cost of major repairs. Turbine accessibility can be addressed through next generation crew transfer vessels which are able to operate in more challenging met-ocean conditions (wave height up to 2.5-3 metres), as well as ensuring that all critical components are easily accessible to reduce the time spent offshore. Better weather monitoring can help to identify appropriate conditions and periods for offshore maintenance visits.

Reducing offshore operations is best tackled by improving reliability to reduce the level of maintenance required. Low maintenance can be designed into the whole system, for example by reducing the number of offshore visits to the structure through the use of improved condition monitoring and remote control systems.

Replacing heavy turbine components is another critical area. Conventional fixed-bottom offshore wind turbines use special-purpose crane vessels to conduct major repairs, which may also need to be adopted in floating wind, though the charter rates for such vessels is particularly high. Undertaking such operations is also sensitive to weather conditions, particularly given the greater degree of movement expected in floating wind structures. A potential lower cost and unique solutions for floating wind turbines would involve transporting the full structure back to shore for port-side maintenance, using considerably cheaper tug boats. However, this remains conceptual and has yet to be demonstrated. In particular, mooring systems and electrical cables will need to be designed for a quick disconnection and reversible installation process that does not impact on the operation of the other units in the wind farm array.

If port-side repairs are possible and cost-effective for floating wind farms, the availability of nearby port infrastructure could become a challenge, particularly given that unscheduled repairs may be required at short notice. Gaining visibility of local shipyard availability can help operators to plan maintenance accordingly.

Table 3.4.1. Key O&M challenges

Challenge	Mitigation
Accessing wind turbines in difficult sea-states	Crew transfer vessels which can operate in more challenging met-ocean conditions
	Design the unit to allow easy inspection and maintenance at sea. All critical components should be above water level and reachable.
	Weather monitoring
System reliability	Low maintenance designed into whole system
	Remote control systems and conditioning monitoring to reduce offshore visits
Replacing heavy turbine components	Special-purpose cranes, or transport structure to shore
	Mooring system, electrical cable connection and other systems should all be designed to accommodate a quick disconnect and reversible installation process. This includes ensuring that all units, upstream and downstream of a disconnected unit, can continue operating.
Availability of local infrastructure for port-side repairs	Visibility on the availability of local shipyards

3.5 Cost Analysis

IMPORTANT DISCLAIMER: The cost data analysed in this study consists of estimates submitted by concept designers. As such, the data has not been validated and carries uncertainty.

Capital Expenditure (CAPEX):

- High CAPEX for early full-scale demonstrations, but considerable cost reduction potential moving to pre-commercial and commercial scale deployments across all components, particularly the platform, turbine, and balance of system.
- Leading concepts estimate CAPEX of ~£2.4m /MW at commercial scale.
- Average CAPEX at commercial scale is similar for all three main typologies; although individual analysis suggests lowest CAPEX in the leading semi-submersible concepts.
- Analysis of the more mature concepts indicates that the CAPEX for spar-buoys may be higher, largely attributed to higher installation costs.
- Similar CAPEX breakdown for semi-subs and TLPs, with slightly lower platform and mooring & anchoring system costs in TLPs negated by higher installation costs.
- Comparison of steel-only concepts implies higher average platform CAPEX for semi-submersibles.
- Concrete structures record lower CAPEX figures than steel concepts, on average.

Operational Expenditure (OPEX):

- Significant reduction in OPEX from prototype to pre-commercial and commercial scale.
- Limited availability of OPEX figures implies a high degree of uncertainty.
- OPEX might be lower for semi-submersible concepts, since they are more amenable to port-side repairs, but this is not yet fully understood and requires further work to understand the technical feasibility and cost benefit of such an O&M strategy.

Levelised Cost of Energy (LCOE):

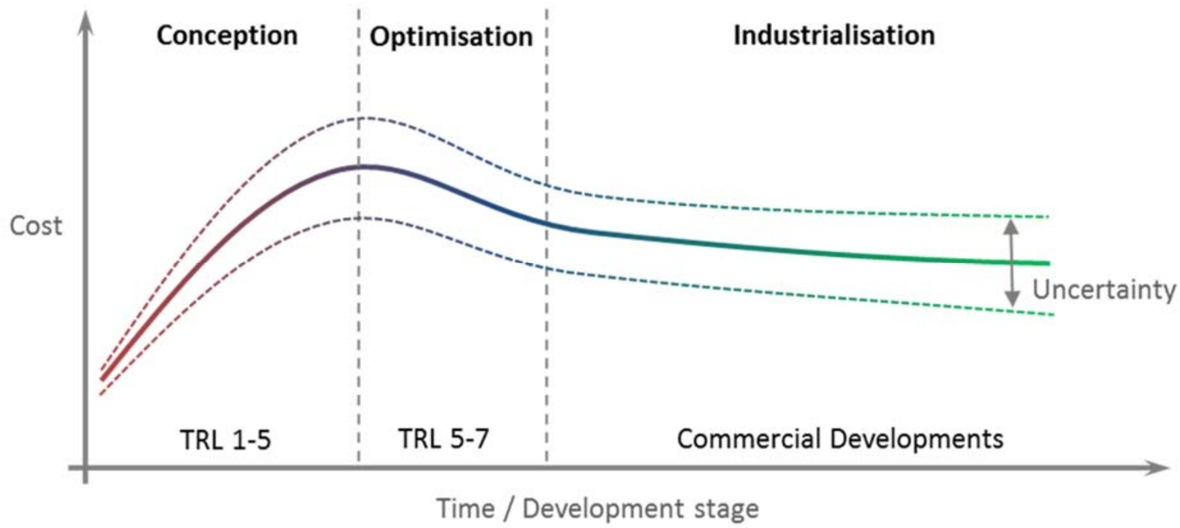
- Marked cost reduction from ~£177/MWh in prototypes to ~£93/MWh in commercial projects, on average.
- Leading concepts suggest LCOE of ~£85/MWh is possible at commercial scale.
- Further cost reduction possible if stronger wind speeds can be accessed.
- Wake effects and energy yield in commercial arrays need to be better understood.
- LCOE is slightly lower for a handful of semi-submersible concepts, largely driven by lower installation costs.
- Spar and TLP concepts could deliver lower foundation CAPEX, but need to optimise installation procedures to reach lower LCOE.
- LCOE is also lower, on average, for concrete designs than the steel alternatives.
- Caution should be taken when analysing the data and a more thorough interrogation of the cost estimates is needed to fully assess and benchmark individual concepts.

Data Uncertainty

The uncertainty associated with the data is largely associated with the nascent state of the technology. Very few floating wind devices have been deployed at full-scale and those which have consist of single prototype demonstrations, which have not had to contend with the additional challenges encountered in commercial-scale deployments, such as high voltage electrical transmission, wake effects, batch fabrication and installation procedures, O&M, logistics, etc.

Furthermore, Carbon Trust experience suggests that the cost of innovative technologies can increase from initial conception to demonstration phase, before falling as the design is optimised and deployment increases (figure 3.5.1). Given that most of the concepts assessed are in the early stages of development (TRL 1-5) and may be nearer the beginning of this cost curve, it is possible that the cost estimates in the following analysis underestimate the full costs of deploying the technology. As such, readers should account for the uncertainty associated with these estimates.

Figure 3.5.1. Technology cost evolution through time



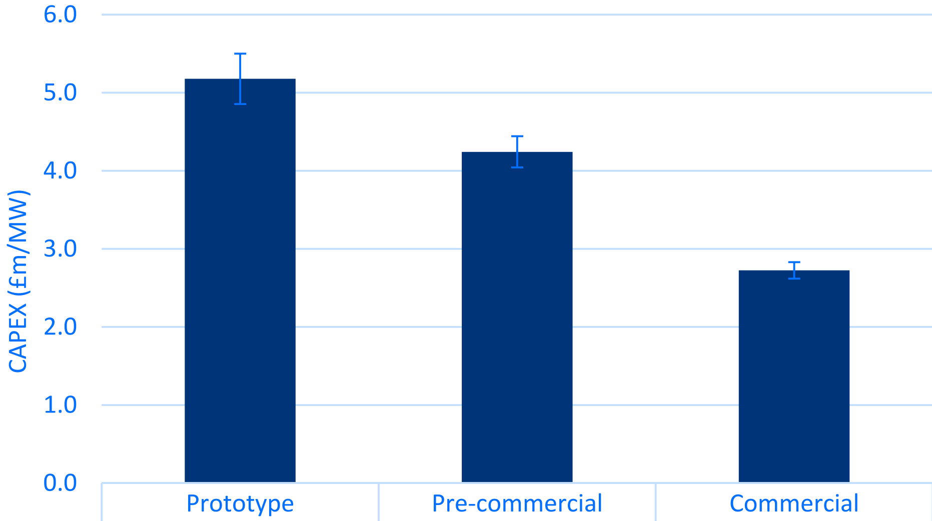
N.B. TRL definitions can be found in table 4.1.1.

It should also be acknowledged that fixed-bottom offshore wind technology is currently more advanced along this cost curve, currently at the beginning of the industrialisation development stage, although further optimisation is still ongoing, particularly technology for more challenging site conditions. The cost of fixed-bottom offshore wind is therefore expected to continue falling over time, and floating wind technology will need to accelerate its development and cost reduction to keep pace.

3.5.1 Capital Expenditure (CAPEX)

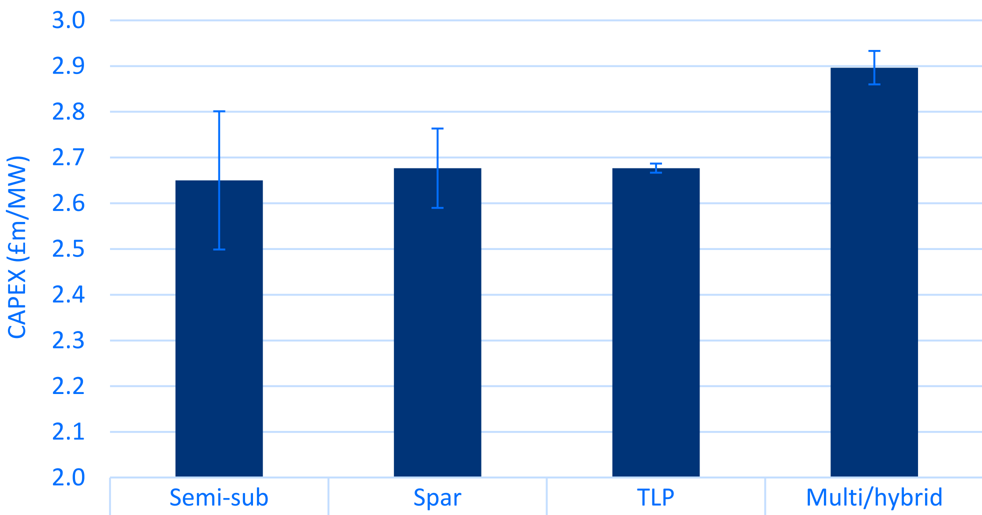
The current cost of floating wind is understandably high, and this is reflected in the CAPEX figures for single prototypes, calculated at ~£5.2m/MW for a single 6 MW demonstration (figure 3.5.2). However, there is significant potential for cost reduction as the scale of deployment increases, with CAPEX reaching ~£4.2m/MW for pre-commercial arrays of ~5 x 6 MW turbines and below £3m/MW for commercial deployments. The commercial CAPEX values for floating wind is even lower if one only considers the three dominant typologies – semi-submersibles, spars, and TLPs – each of which expect to deliver commercial projects at just under £2.7m/MW, on average (figure 3.5.3). An assessment of individual concepts suggests that CAPEX could be as low as £2.4m/MW for the cheapest devices.

Figure 3.5.2. CAPEX for floating wind devices at prototype, pre-commercial, and commercial scale



	Prototype	Pre-commercial	Commercial
CAPEX /MW	5.2	4.2	2.7

Figure 3.5.3. Commercial-scale CAPEX for floating wind typologies

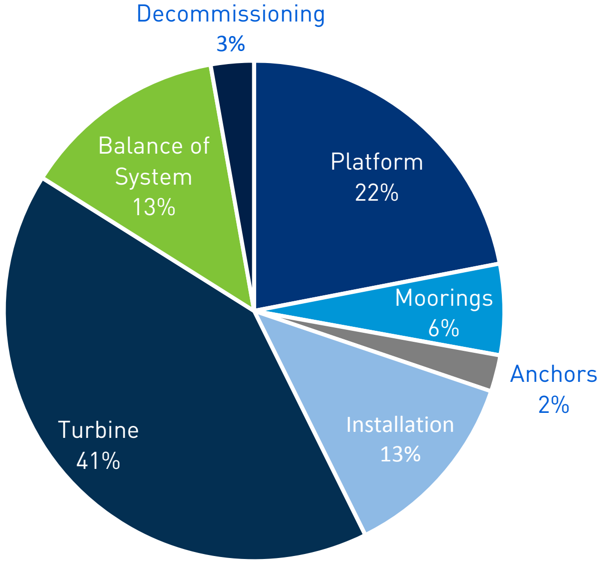


	Semi-sub	Spar	TLP	Multi/hybrid
CAPEX /MW	2.65	2.68	2.68	2.90

CAPEX breakdown

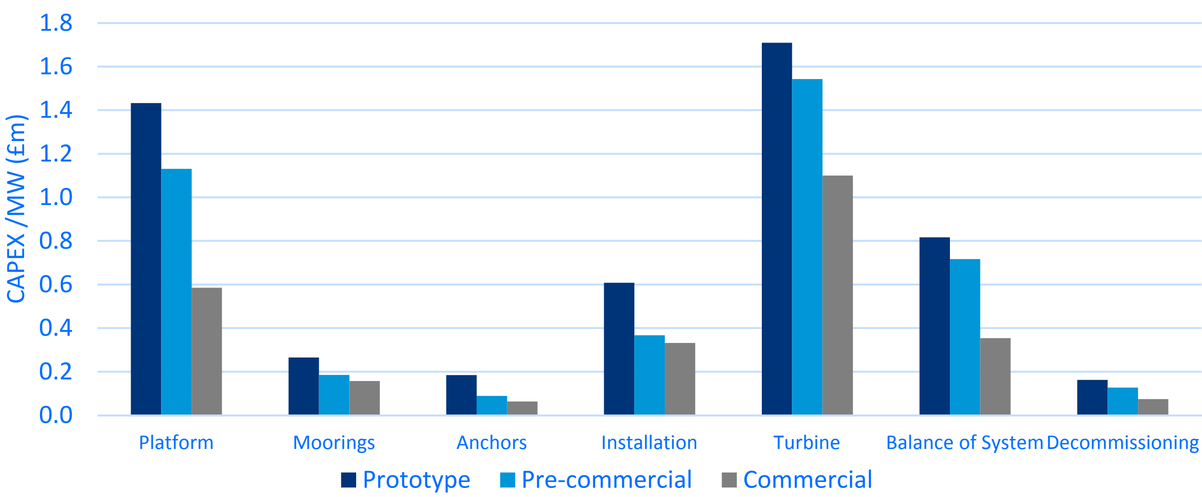
The greatest share of the overall CAPEX comes from the turbine (41%) (figure 3.5.4), followed by the platform (22%) and balance of system (13%), which includes the costs of the electrical infrastructure (i.e. substation, cables, grid connection), project development and management (i.e. consenting), and contingency. Installation costs are also significant, representing ~13% of CAPEX in commercial wind farms, though this is considerably lower than installation costs for fixed-bottom offshore wind projects, which can reach up to 20% of CAPEX. The combined cost of the moorings and anchors makes up ~8% of the total CAPEX, while decommissioning costs are relatively minor, at just 3% of capital expenditure.

Figure 3.5.4. CAPEX breakdown for a commercial scale floating wind farm



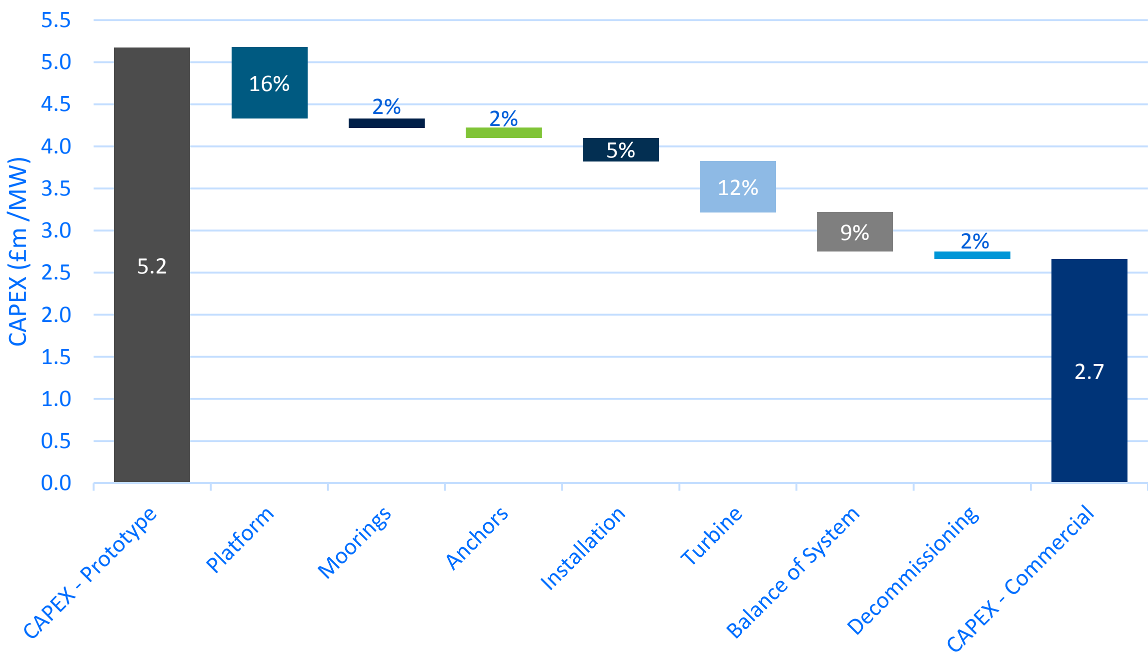
There is considerable cost reduction potential across all major components as floating wind technology moves from prototype to commercial stages of development (figure 3.5.5). The greatest absolute reductions are evident in the turbine, platform, and balance of system; although there are considerable relative reductions in installation and anchor costs.

Figure 3.5.5. CAPEX breakdown by component for different deployment scales



To reduce the cost of floating wind and reach parity with other forms of energy generation, cost reduction will need to be achieved across the full project lifecycle. It is expected that the greatest cost reduction will be achieved in the platform (16%), turbine (12%), and balance of system (9%), but there is also considerable scope for cost reduction improve installation procedures (5%) and optimise mooring and anchoring systems (4%) (figure 3.5.6). Cost reduction efforts will need to address all of these areas, delivering cost reduction through a combination of learning by doing, targeted RD&D initiatives, and benefitting from economies of scale (see section 5 for more on recommendations for future RD&D activities).

Figure 3.5.6. Cost reduction from prototype to commercial scale

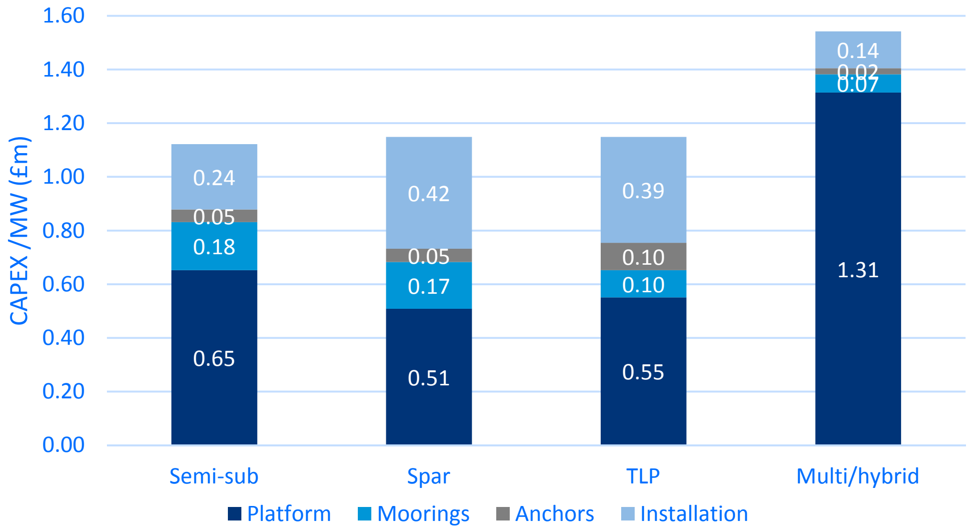


N.B. Percentages represent share of overall cost reduction. Analysis of the three main typologies only (semi-sub, spar, TLP). Assumes consistent 6 MW turbine capacity, so does not account for cost reduction from increasing turbine power.

To undertake a fair comparative analysis of capital expenditure between concepts, values for the cost of the turbine, balance of system, and decommissioning were kept constant. CAPEX variations between typologies is therefore driven by differences in the cost of the platform, moorings, anchors, and installation. A breakdown of these costs is given in figure 3.5.7.

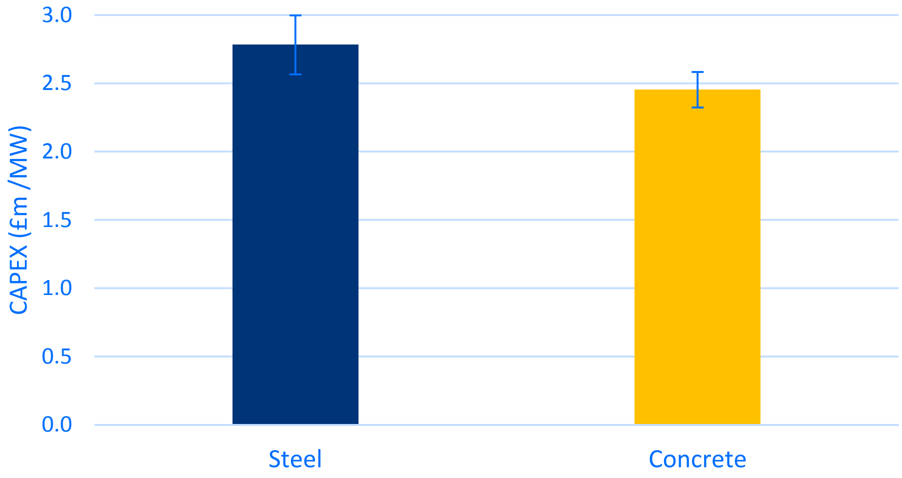
Despite attaining a similar total CAPEX, there are marked differences in the cost breakdown of the three main typologies. Spar-buoys achieve a lower platform cost, due to the lower grade of steel required and the suitability of the simple cylindrical design to serial fabrication processes. However, these cost savings are negated by high installation costs, attributed to the need to assemble the turbine offshore using expensive heavy lift vessels. The more mature spar concepts indicate higher costs in all areas, making them less competitive against other designs.

Figure 3.5.7. CAPEX breakdown (variable metrics only) by typology



Semi-submersible and TLP concepts appear to be more aligned in their cost breakdown. However, while platform costs are similar when averaged across all concepts, it should be noted that a comparison of steel-only concepts revealed higher costs for semi-submersible platforms than TLPs, which is unsurprising given the additional steel used in the designs (see figure 3.1.2). Concrete designs analysed across all typologies derived a lower CAPEX, on average, than the steel alternatives (figure 3.5.8).

Figure 3.5.8. CAPEX of steel vs. concrete concepts (commercial scale deployment)

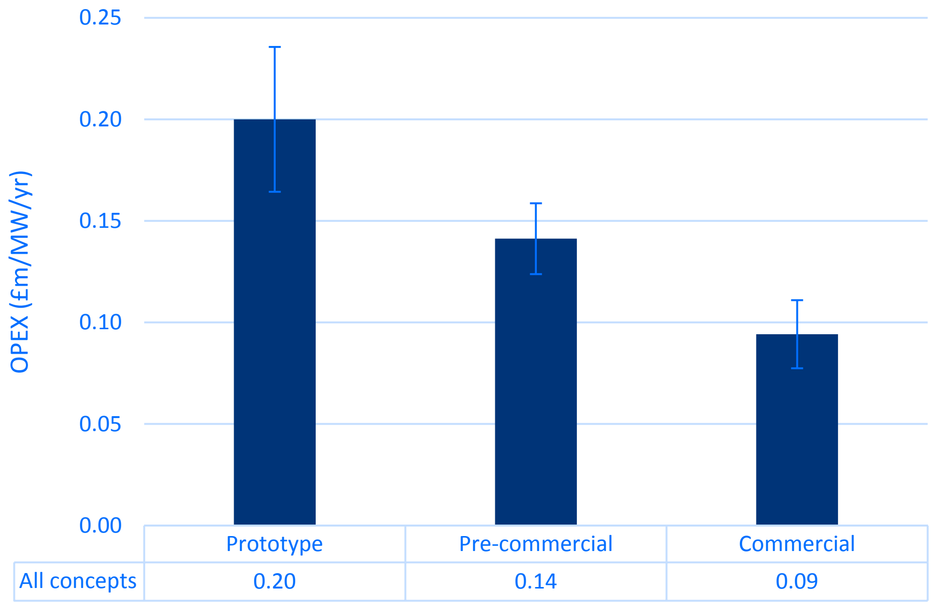


Semi-submersibles deliver the lowest installation costs of three main typologies, due to the ability to conduct full assembly onshore and the limited vessel requirements to conduct installation. Anchor costs are also low, by using lighter and cheaper drag-embedded anchors, though this is countered by the additional cost of long catenary mooring chains. Conversely, the shorter moorings used in TLPs result in a net reduction in mooring costs, but the increased vertical loading and additional holding capacity required places greater forces on the anchors, which are more expensive than other concepts. Analysis of only the more mature TLP concepts indicates a lower platform cost but considerably higher installation costs; though the net impact delivers a similar total CAPEX, on par with semi-submersibles.

3.5.2 Operational Expenditure (OPEX)

Like capital expenditure, there is significant potential for operational costs to come down as deployment increases in scale (figure 3.5.9). Economies of scale associated with larger wind farms sizes results in an OPEX reduction of over 50% from prototype to commercial scale, reaching less than £100k/MW/yr. OPEX values were kept constant for the different concepts, largely due to the lack of quality data submitted, which implies that O&M is an area which requires significant further research for floating wind concepts. However, it is possible that OPEX may be lower for semi-submersible concepts due to the greater ease of conducting major turbine repairs by towing the full structure back to port, thereby mitigating the cost of expensive heavy lift vessels, which must be used by spar-buoy devices. TLPs can also be towed back to shore for maintenance, but the added complexity of the mooring system and lack of buoyancy stability contribute to higher costs. Bespoke barges may be required and weather restrictions will constrain operations. However, further studies will need to be conducted to first understand the technical viability of major port-side repairs and then understand the cost benefit of doing so for different concepts.

Figure 3.5.9. OPEX for floating wind devices at prototype, pre-commercial, and commercial scale



3.5.3 Levelised Cost of Energy (LCOE)

With the same assumptions made for OPEX, yield, and power output, the trends seen in the CAPEX figures run through to LCOE, revealing marked cost reduction from ~£177/MWh in early prototypes to ~£93/MWh in commercial projects (figure 3.5.10), below the current cost of energy target for the fixed-bottom offshore industry by 2020. An assessment of individual concepts shows even greater cost reduction potential, with LCOE reaching as low as ~£85/MWh for the leading designs. The three main typologies display similar LCOE values, with LCOE for semi-submersible, spar, and TLP concepts at ~£92-93/MWh for commercial projects, although there is greater variance in semi-submersible and spar-buoy concepts (figure 3.5.11). Multi/hybrid concepts are generally more expensive than the other typologies, although there are more competitive concepts within the range of data.

Figure 3.5.10. Levelised cost of energy for floating wind projects, at prototype, pre-commercial, and commercial scale

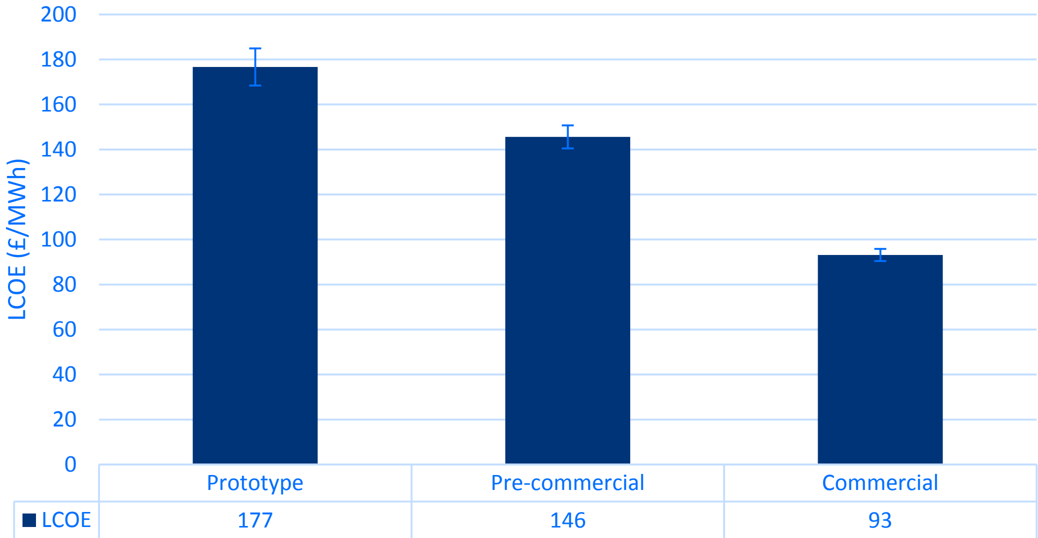
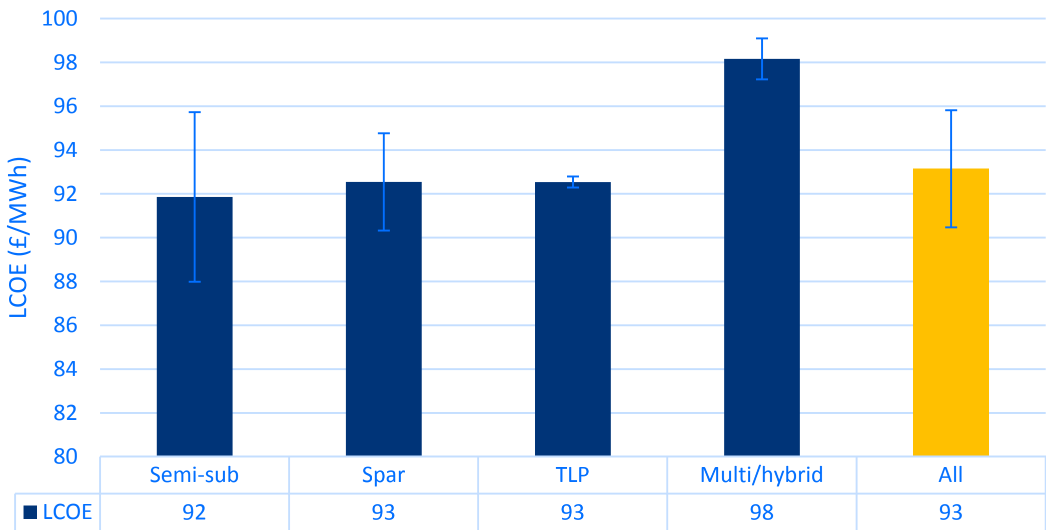
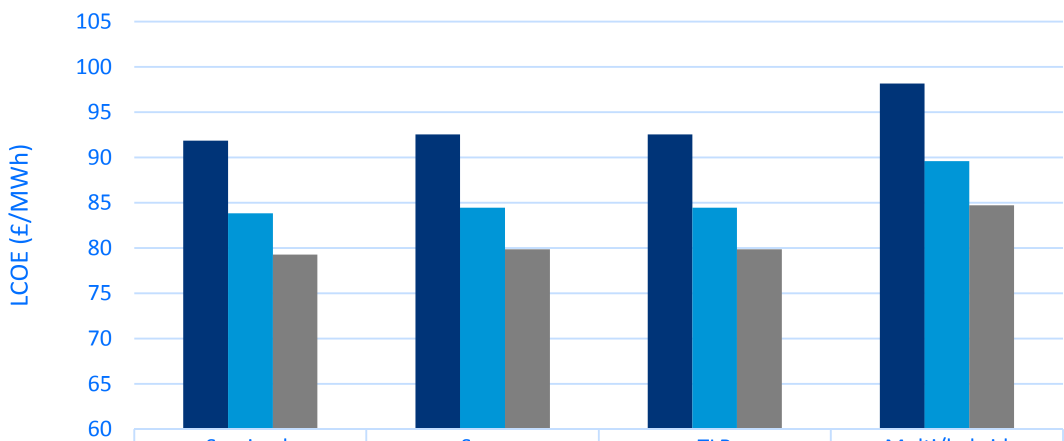


Figure 3.5.11. Levelised cost of energy for commercial scale floating wind projects



LCOE is highly sensitive to wind speed and can therefore improve even further if stronger wind resource can be accessed and fully captured. The LCOE values stated above were calculated based on an average annual wind speed of 9.7 m/s, but increasing the average wind speed to 10.5 m/s and 11.4 m/s delivers further reduction of 9% and 14% respectively (figure 3.5.12). At the highest wind speeds, this could reduce the average cost of energy to ~£80/MWh in semi-subs, spars, and TLPs, and as low as £73/MWh for the most promising concepts.

Figure 3.5.12. LCOE for commercial-scale floating wind projects at different average wind speeds



	Semi-sub	Spar	TLP	Multi/hybrid
9.7 m/s	92	93	93	98
10.5 m/s	84	84	84	90
11.4 m/s	79	80	80	85

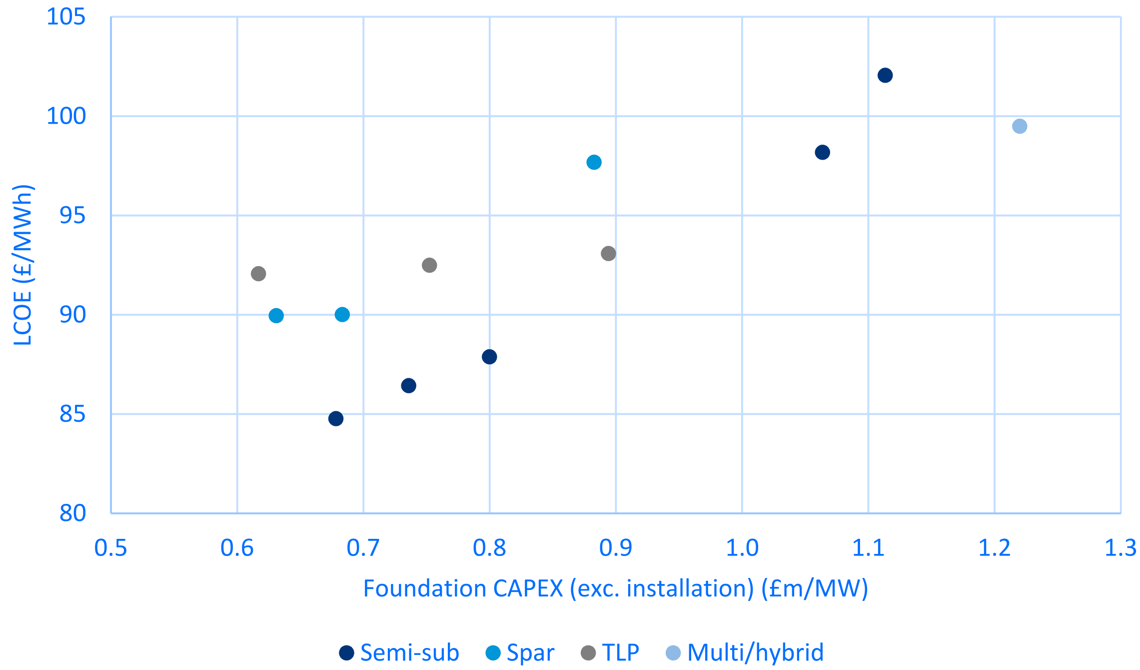
N.B. Wind speed and yield data sourced from Glosten Associates (2014).

Grouping costs by typology can be somewhat misleading, given that the cost of energy is variable between the concepts within each typology. The spread of the data is presented in figure 3.5.13, which plots the LCOE and foundation CAPEX[1] of individual concepts. Given that OPEX, yield, and energy output are assumed to be constant in this analysis, cost reduction is driven by reduced CAPEX, shifting the plots towards the bottom-left of the chart. Variance in the CAPEX-to-LCOE relationship is driven by different installation costs, which is not included in the foundation CAPEX.

There is a broad range of cost estimates between concepts, particularly between semi-submersibles, which have the three lowest cost designs (by LCOE), as well as two concepts with some of the highest CAPEX values. The CAPEX variance between semi-subs appears to reflect the primary material used in the structures and the degree of optimisation to reduce platform size. LCOE variance between semi-submersible and other typologies is driven by the lower CAPEX expected for installation. Spar-buoy and TLP concepts can deliver low foundation CAPEX, but the higher installation costs drive up LCOE. Overcoming installation challenges is therefore of critical importance for spar and TLP devices. It should also be noted that most of the concrete designs analysed were in the lower end of the cost range.

[1] Foundation CAPEX includes the platform, moorings, and anchors (i.e. excludes installation, turbine, BOS, decommissioning).

Figure 3.5.13. LCOE and CAPEX of commercial-scale floating wind projects



While caution should be taken when analysing cost data submitted by designers, the LCOE cost data supports the case that floating wind can reach cost parity with fixed-bottom offshore wind and be a highly competitive source of electricity generation in the UK's future energy mix. Even the higher ranges of the cost data – which may be considered more realistic prospects for commercial deployments in the 2020s – are close to the desired £100/MWh mark for fixed-bottom offshore wind by the end of this decade. It should also be noted that this data refers to commercial sites with a 6 MW turbine capacity, and further cost reduction can be expected as power output increases to 8 MW and 10 MW per unit. However, public funding support will be required to advance the technology and commercialise floating wind devices if these cost savings are to be realised.

4 Technology Readiness

TRL Status:

- TRL progression has been slower than anticipated for many concepts, largely due to the 'valley of death' from scaled modelling to full-scale demonstrations.
- 25 concepts have conducted scaled testing (TRL-3), but only 5 of these have installed full-scale prototypes (>1 MW or equivalent).
- The step from TRL-3 to TRL-4 typically takes around twice as long as other TRL progressions.
- However, a number of demonstrations are in the pipeline, with several multi-megawatt demonstrations and pre-commercial arrays expected over the next few years.
- Challenge of undertaking full-scale demonstrations and limited market for floating wind at present is likely to see consolidation in the market, with perhaps up to 10 different concepts competing to reach commercial status.
- Semi-submersible and spar-buoy concepts are currently more mature than TLPs and are likely to reach commercial status sooner.

Investment to commercialise:

- Up to £30m is expected to be needed to develop floating wind concepts from initial conception to commercial deployment.
- Public funding support is vital to overcome the 'valley of death' between TRL-3 and TRL-4 (full-scale demonstration).
- Many early stage concepts are underestimating the levels of investment required, which may contribute to some devices falling by the way side if industrial partners cannot be sought.
- Need to create a market and engage developers to 'pull' the technology to commercialisation.

Target markets:

- Scotland and the wider UK are a seen as an attractive market by floating wind designers.
- Significant potential in other European markets, particularly in Portugal, France, and other Mediterranean locations.
- USA and Japan have enormous potential for floating wind and are also being targeted by many concept designers.

4.1 Technology Readiness

Technology readiness levels (TRL) are a key indicator for how advanced a technology is on its path to commercialisation. Any technology must progress through a series of incremental milestones to validate the performance of the design, with testing at steadily increasing scales from part-scale prototype to full-scale application in relevant environmental conditions. This study has set TRL levels according to the Lloyd's Register Guidance Note for Technology Qualification (Lloyd's Register, 2014) and fine-tuned the milestones such that they are relevant to floating offshore wind (table 4.1.1).

Table 4.1.1. TRL definitions and milestones

TRL Level	Milestone
0. Unproven concept	Idea / preliminary study / patent
1. Proven concept	Desk-based basic design assessment / proof of concept
2. Validated concept	Detailed numerical modelling / structural assessment
3. Prototype tested	Scaled testing (e.g. tank testing, <1 MW demonstration)
4. Environment tested	Offshore demonstration with 1-5 MW turbine
5. System tested	Full-scale offshore demonstration/array with >5 MW turbine
6. System installed	Full-scale demonstration/array with >5 MW turbine with >1 year operation
7. Field proven	Commercial project

Floating wind concepts must all pass through these stages in order to reach commercial acceptance by certification bodies and give confidence to investors. Initial concepts will begin as an idea, before undergoing some basic and then detailed numerical modelling and design assessments to prove the viability of the concept and make improvements to the design. Once proof of concept has been attained, concepts will undergo scaled testing to assess their performance in an offshore environment. This will most likely take the form of tank testing, where wind and wave conditions can be simulated in a controlled environment, though some concepts will also undertake more advanced testing with an offshore installation of a small-scale prototype (<1 MW). The next stage is an offshore demonstration, with a 1-5 MW turbine, followed by a full-scale demonstration, or first array, with a turbine with >5 MW power output. This demonstration will then need to prove its performance with at least one year of operation and testing. If results are satisfactory, the device can be considered ready for commercial application.

TRL status of floating wind concepts

The TRL status of the various floating wind concepts currently under development is shown in table 4.1.2. As can be seen, the majority of concepts – 25 in total – have progressed beyond numerical modelling (TRL 2) to undertake scaled testing of their respective devices (TRL 3). However, very few concepts – only 5 – have made the next critical step to a multi-megawatt offshore demonstration, highlighting the step change in financing required at this stage of development, which represents the 'valley of death' for technology designers. It should be noted that a handful of concepts at TRL 3 have conducted more advanced scaled testing with small scale prototypes (<1 MW) in an offshore environment (e.g. VoturnUS, Sway, Poseidon), and can be considered to have reached a higher technology readiness level than other concepts in the TRL 3 bracket, but this again highlights the challenge of moving straight from tank testing to full-scale demonstrations.

A number of concepts are planning full-scale demonstrations over the next few years; although there is no guarantee that all of these will succeed in securing test sites, securing public subsidies, and reaching financial close. Most will be demonstration in the 1-5 MW range, though some concepts with strong industrial backers will bypass TRL 4 to conduct demonstrations of 5+ MW demonstrations (e.g. MHI V-shape semi-sub; DCNS SeaReed). A few of the more advanced concepts which have already installed full-scale units will look to develop the first pre-commercial arrays (e.g. Statoil Hywind; Principle Power WindFloat).

The challenges of progressing to TRL levels 4 and 5 and the limited amount of public support available, together with the success of early movers, is likely to see consolidation in the market with a number of concepts falling by the way side. Thus, the current field of ~30 designs is likely to be whittled down to ~10 leading concepts competing to secure commercial deployments. No single concept is expected to emerge as a winner, but a variety of concepts suitable to different site conditions and developed in different markets.

Table 4.1.2. TRL status of floating wind concepts

	Manufacturer	Concept	TRL 0 Initial concept	TRL 1 Proof of concept	TRL 2 Numerical modelling	TRL 3 Scaled testing	TRL 4 1-5 MW demo	TRL 5 >5 MW demo	TRL 6 >1 year operation	TRL 7 Commercial project
Semi-submersible	Principle Power	WindFloat						2017		
	Mitsui Eng. & Shipbuilding	Compact semi-sub								
	Mitsubishi Heavy Industries	V-shape semi-sub						2015		
	DCNS	SeaReed						2018		
	IDEOL	IDEOL					2015			
	Nenuphar	Vertiwind					2016			
	DeepCWind Consortium	VolturnUS					2018			
	GustoMSC	Tri-Floater								
	GustoMSC/Eolfi	Spinfloat								
	Nautilus Floating Solutions	Nautilus								
	TetraFloat Ltd.	TetraFloat								
	Aerodyn Engineering	SCD Nezzy				2015				
Spar-buoy	Statoil	Hywind						2017		
	Japan Marine United	Advanced spar					Substation	2016		
	Toda Construction	Hybrid concrete-steel spar						TBC		
	Sway AS	Sway								
	Catalunya University	Windcrete								
	SeaTwirl Engineering	SeaTwirl								
	DeepWind Consortium	DeepWind spar								

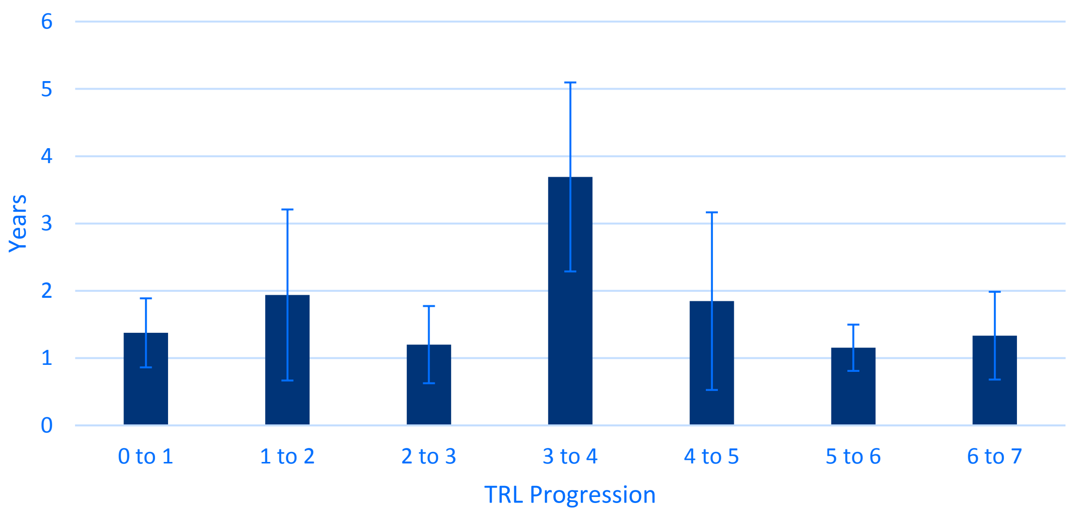
	Manufacturer	Concept	TRL 0 Initial concept	TRL 1 Proof of concept	TRL 2 Numerical modelling	TRL 3 Scaled testing	TRL 4 1-5 MW demo	TRL 5 >5 MW demo	TRL 6 >1 year operation	TRL 7 Commercial project
TLP	GICON/ESG	GICON-SOF					2015			
	Glosten Associates	PelaStar								
	Blue H Engineering	Blue H TLP								
	DBD Systems	ECO TLP								
	Iberdrola	TLPWind								
	Nautica Windpower	Advanced Floating Turbine								
Multi/hybrid	Floating Power Plant	Poseidon P80								
	Riam/Kyushu University	WindLens								
	MODEC	SKWID								
	Hexicon AB	Hexicon				2015				
	WindSea AS	WindSea								
	W2Power	W2Power								

N.B. Dark blue corresponds to TRL levels which have already been reached. Light blue corresponds to planned future activity. Only announced future activity that is deemed to be likely to proceed has been included (i.e. test site secured; financing secured (part or full)).

Rate of development for floating wind concepts

The 'valley of death' between TRL levels 3 and 4 is evident in figure 4.1.1, which shows the average time taken to progress between TRL levels. The data includes both actuals and estimates for future projections. Progressing along TRL levels 0-3 is fairly quick due to the relatively low cost of conducting numerical modelling and small-scale tank testing. However, moving from TRL 3 to 4 typically takes double the amount of time, often more, and assuming that this stage is reached at all. Many of the designers contacted were unable to state when a full-scale demonstration will take place. The responses received are also considered to be fairly ambitious timelines for concept development. In reality, a number of full-scale demonstrations will either be cancelled or pushed back by a year or more.

Figure 4.1.1. Average progression time between TRL levels

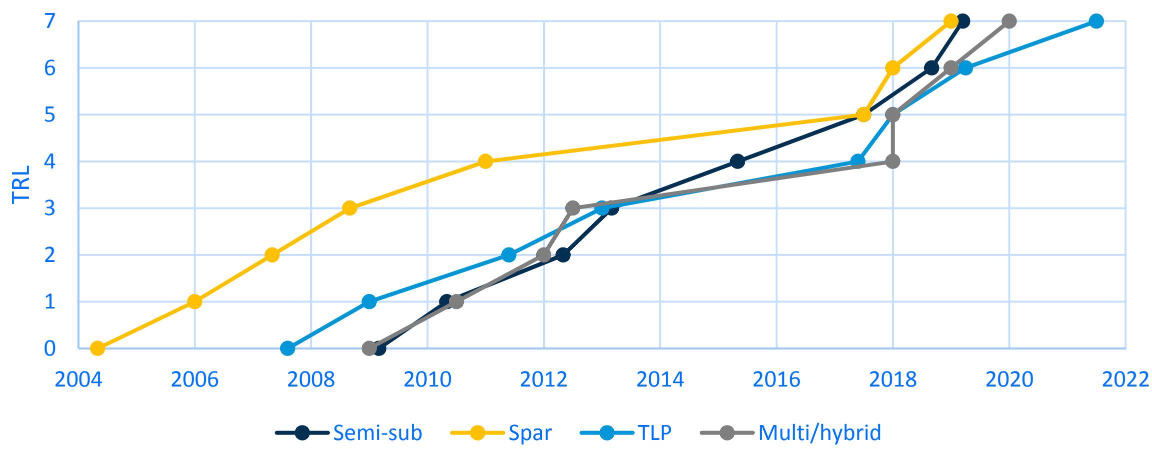


The challenge to finance full-scale demonstrations is partly exacerbated by the conservative – and therefore more expensive – designs used in early prototypes. Over time it may be possible that advanced modelling and tank testing could help to close the large gap between TRL levels 3, 4, and 5. It is acknowledged that, given the lack of offshore demonstrations to validate numerical modelling tools and tank test performance, there remains a higher level of uncertainty that leads to greater risk and more conservative designs. However, as coupled modelling tools are improved and concepts can be optimised with greater confidence at the tank testing phase, it may be possible for more concepts to leapfrog the TRL-4 phase and move directly to 5+ MW demonstrations and pre-commercial arrays. More advanced tank testing facilities and numerical modelling tools may be required to unlock this.

The excessive costs of prototype demonstrations is also largely attributed to the additional costs for project development, consenting, grid connection, and vessel mobilisation for installation of just a single device. Meanwhile, moving to pre-commercial projects with more devices adds financing challenges by increasing the level of capital required for developers. Given the high costs involved and the limited infrastructure available for demonstration projects, public funding could be used to create a test facility with testing berths for multiple devices, similar to the EMEC facility for wave and tidal technologies. Such an approach would socialise the development costs across a number of users and enable the validation and benchmarking of multiple concepts. The proposed test centre at Dounreay could be designed to adopt this approach.

The over-ambitious nature of the development projections of a number of designers is also evident in the rate that they expect to reach later stages of technology readiness and commercial application. The modest timescales envisaged by many designers indicates that floating wind devices could be used in commercial projects as early as 2019 (figure 4.1.2). In reality, commercial floating wind projects are not expected until beyond 2020, once the technology has been field proven and the cost reduction potential has been demonstrated. There will also need to be a market for floating wind with interest from developers to introduce the large volumes of private funding required to take floating wind technology to the commercial stage. As an example of the slow timelines involved, one should note that despite a full-scale demonstration in 2009, the Hywind concept has failed to secure a 5+ MW demonstration since, with a pre-commercial array using 6 MW turbines planned for 2017, 8 years after the initial 2.3 MW installation.

Figure 4.1.2. TRL progression over time (average of actuals and estimates of future projections)



Despite the ambitious development timelines envisaged, the trend observed is quite plausible. Spar-buoys, followed by semi-submersibles, are the more advanced technologies, having reach TRL 4 status before the other typologies. Spar-buoy and semi-submersible concepts are also expected to reach commercial status first. Despite the emergence of a number of TLP concepts, the lack of a full-scale demonstration means that the technology is a few years behind that of the more established spars and semi-subs. The additional risk associated with more nascent technologies may prove a barrier for TLPs when seeking investment for full-scale demonstrations; although this isn't to say that individual concepts may break this trend with the right support. Projections for multi/hybrid concepts are considered to be markedly over-ambitious, with technology readiness at a far earlier stage than the other concepts and commercial status not expected until well beyond 2020.

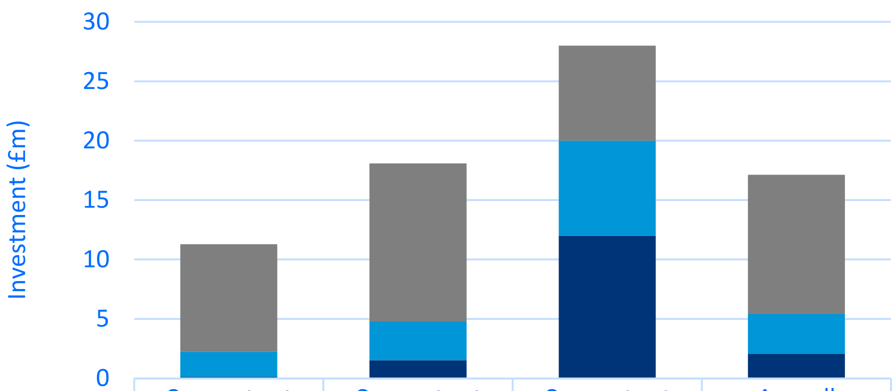
4.2 Investment to Commercialise Devices

In addition to development timescales, it appears that lower TRL designers are also underestimating the additional funding required to commercialise their devices. There is a clear trend in the level of investment anticipated increasing in line with technology readiness status, from a total investment cost of £11.3m in TRL-2 concepts to £28.0m in TRL-4 concepts (figure 4.2.1). It is therefore important that designers properly account for the 'hidden' costs and extended timescales of developing floating wind devices.

There is also a trend in the mix of public and private sector investment received. At the early development stages (TRL-2), private investment is dominant in supporting desk-based design modelling, with very little public support provided. Public funding increases at TRL-3 to conduct testing of small-scale prototypes, though this is matched with a similar level of additional private input. However, public funding increases substantially in the progression to TRL-4, where the cost of full-scale offshore demonstrations increases dramatically, leveraging significant private funding in the process. This reinforces the need for government support at this stage of development, to push the technology to the market. Once full-scale demonstrations have been conducted and the devices have been field proven, private investment is expected to dominate, to pull the technology to market.

Given the limited amount of public funding available, it is important to shift the market push-market pull transition to as early a stage as possible. For this to occur, a clear market needs to be created for floating offshore wind. In the UK, developers are currently focussed on fixed-bottom offshore wind sites; however, highlighting and demonstrating the cost competitiveness of floating wind in deep water sites close to shore (<50 km) with strong wind resource could encourage developers to take a greater interest and involvement in floating wind technology.

Figure 4.2.1. Investment to date (public & private) and additional funding required for concepts at different TRL levels

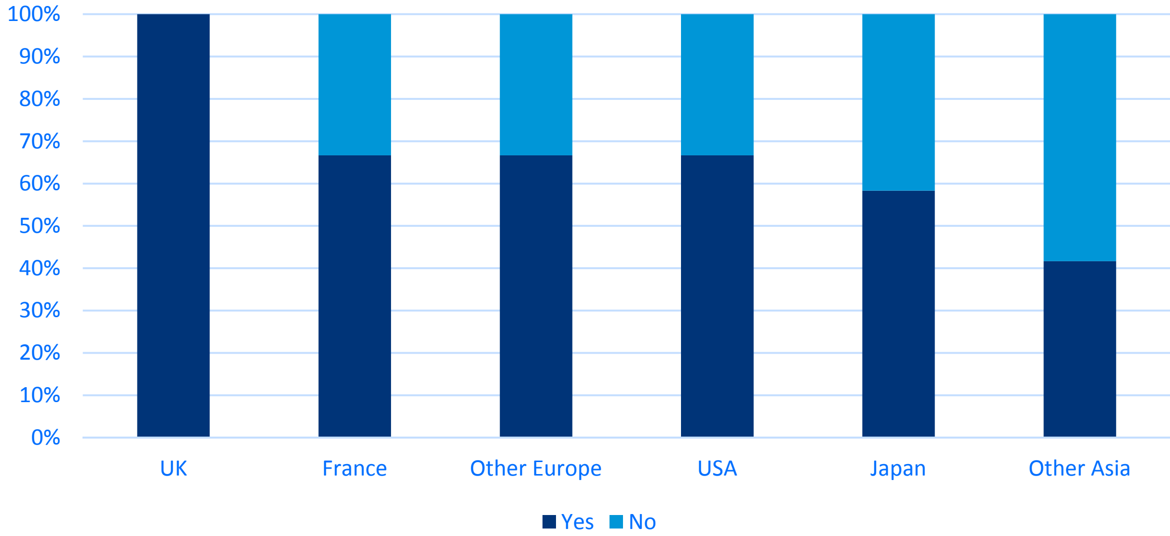


	Concepts at TRL-2	Concepts at TRL-3	Concepts at TRL-4	Ave. all concepts
TOTAL	11.3	18.1	28.0	17.1
Additional required	9.1	13.3	8.0	11.7
Private spend to date	2.1	3.3	8.0	3.4
Public spend to date	0.1	1.5	12.0	2.0

4.3 Target Markets

The UK – and Scotland in particular – is certainly seen as an attractive market by floating wind designers, targeted by all respondents to the Carbon Trust's request for information (figure 4.3.1). France and other European markets, such as Portugal and other countries in the Mediterranean, have also been identified as potential markets for floating wind technology. This is not surprising given Europe's leading position in fixed-bottom offshore wind. However, designers are also targeting the emerging markets in the USA and Japan, in addition to other Asian markets, such as China, South Korea, and Taiwan, where significant offshore wind resource is located in deep water locations (>60m). Given the flexibility of the application of floating wind concepts and the lack of an established market to date, most designers are expected to take a global approach, entering the markets which offer the most attractive government support and local industrial partners. Scotland, and other parts of the UK, already have suitable infrastructure and local expertise to accommodate floating wind projects, and are well-placed to take a leading position in floating wind if the right support policies are in place.

Figure 4.3.1. Target markets for floating wind designers



5 Key Challenges and Opportunities

Key technical barriers:

- Prioritisation of the main technical challenges identified platform size as the most critical technical barrier, followed by installation procedures.
- Considerable CAPEX savings are also possible from developing floating transformer stations, advanced control systems, and optimised mooring & anchoring systems.
- Significant OPEX savings are expected from port-side major repairs, though the technical feasibility and cost benefit is currently poorly understood.
- Some challenges are more pressing in the short-term (e.g. advanced modelling tools), while others will become increasingly significant as the technology advances to commercial scale (e.g. floating transformer stations, high voltage dynamic cables, wake effects).
- There is considerable variation between the priorities of different concepts, but also a number of common challenges that could be addressed through collaborative R&D projects, where there is less IP sensitivity.

Key market barriers:

- From a Scottish perspective, the most critical challenge is the absence of a successor subsidy mechanism beyond the October 2018 enhanced ROC deadline.
- This is fuelled by a lack of clarity over the long-term role for both floating and fixed-bottom offshore wind in the UK energy mix.
- The outcome is a lack of market-pull from developers and private investors.
- Private sector adopt a risk-averse approach to moving to a new technology.
- High cost of early demonstration projects and lack of testing facilities is a challenge which requires greater government support.
- Lack of engagement with key players in the supply chain, particularly turbine manufacturers.

RD&D opportunities:

- Opportunities identified for future RD&D activity at four levels:
    1. Concept-specific RD&D to support full scale demonstrations
    2. Test facility development
    3. Collaborative RD&D to overcome common challenges
    4. Evidence-base studies

5.1 Key Technical Barriers

The main technical barriers to commercialising floating wind technology are summarised in table 5.1.1. The Carbon Trust has engaged with leading concept designers to score and prioritise the key challenges, based on their cost reduction potential, urgency/time criticality, and IP sensitivity. Responses were highly variable, particularly in the scoring of the urgency and cost reduction potential of the challenges, which is partly attributed to the variance in prioritisation between typologies, but also possibly highlights a lack of collaboration within industry to share best practice solutions. Nevertheless, some broad trends were evident, as displayed in table 5.1.1, which ranks the challenges in order of cost reduction potential.

The urgency of the challenges identified those which are the most time critical over the short-term. The response data had a small range, with most challenges perceived to be fairly high priority, but the ranking largely mirrors cost reduction potential. However, there a few notable examples, such as floating transformers, which are a longer-term priority that will only become necessary for commercial-scale projects, and advanced modelling software, which, despite limited scope to reduce costs directly, is a critical near-term challenge which can help to unlock cost reduction in other areas.

IP sensitivity was used to identify areas suitable for collaboration, which can highlight common challenges that might be addressed through joint industry projects or collaborative R&D programmes. Thus, while platform size has high cost reduction potential, it is a highly IP sensitive component which is specific to each concept. Other areas, such as port-side O&M strategies, wind farm operation, industry standards, and environmental impact are more amenable to collaboration.

It should be noted that all of the challenges listed are critical barriers to commercialising floating wind, all of which must be addressed if floating wind is to realise its cost reduction potential, and some of which are more important to certain concepts than others. The purpose of this analysis is to identify where R&D efforts could have greatest impact in supporting the industry, by overcoming near-term barriers and those which can have the greatest impact on the cost of energy.

Table 5.1.1. Prioritisation of key technical barriers

Technical challenge	Cost reduction potential	Urgency	IP sensitivity
Platform size & weight	2.7	2.4	2.8
Installation procedures	2.5	2.2	1.8
Port-side O&M (major repair procedures)	2.3	2.2	1.0
Floating substations/transformer modules	2.3	2.0	2.0
Advanced control systems for floating WTGs	2.2	2.2	2.6
Mooring design & installation	2.2	2.1	2.4
Anchor design & installation	2.1	2.1	2.0
Advanced tank testing facilities	2.0	2.1	1.7
Wind farm operation (wake effects, yield, AEP)	1.9	2.1	1.0
Advanced modelling tools	1.9	2.5	2.0
High voltage dynamic cables	1.8	2.1	1.6
Bespoke standards for floating wind	1.8	2.0	1.0
Environmental impact	1.4	2.1	1.0

N.B. Scoring from 1-3; High = 3, Med = 2, Low = 1.

Platform size & weight

The greatest potential for cost reduction is seen in reducing platform size and improving installation procedures. Reducing the size and weight of the floating platform represents an obvious area where CAPEX savings can be achieved by reducing the steel content and complexity of the structure (i.e. suitability to serial production). Our analysis also suggests that using concrete as the primary material could reduce platform costs for some concepts, though this will need to consider expected lead times for concrete structures, which could exceed those of steel structures. However, reducing structural mass needs to be achieved without compromising the stability of the structure to ensure that tower-top accelerations are minimised.

Installation

Installation is another major cost driver which requires further optimisation. Just as this is relevant to single installations, increasing scale of deployment will need optimised batch installation procedures for multiple devices at a time. This will need to maximise the available weather window for offshore operations, using more advanced tugs and barges as well as better weather monitoring offshore. Installation costs will also be influenced by the availability of suitable port infrastructure for load-out and assembly, as well as for use as an O&M base.

Port-side O&M

Related to this, there is currently no defined procedure for port-side major repairs. It is believed that such an O&M strategy could deliver significant cost savings, but this will require cost-effective methods of unhooking the structure from its mooring and electrical cables, towing it to port, and reversing the process for re-connection. As well as proving the technical feasibility, it will be necessary to understand the cost benefit versus conventional O&M strategies, and how this will vary with distance from shore. This is more relevant to semi-submersible and TLP concepts, and is a far lower priority for spar-buoys, for which port-side repairs are not expected to be feasible.

Floating transformer stations & high voltage dynamic cables

While not an urgent priority, developing floating transformer stations will become a critical cost driver for floating wind farms when deployment is scaled up. Floating substations are expected to be highly costly and may require novel floating platforms to support them. Alternatively, floating platforms may be able to adopt offshore transformer modules, which is currently being pioneered in fixed-bottom offshore wind farms. Developing high voltage dynamic cables will also be tied to this, and while 33-66kV cables are already available and operational in existing floating wind projects, moving to higher export cable voltage (e.g. 132kV, 220kV) may present a greater challenge.

Advanced modelling tools

Despite a low scoring on cost reduction potential, advanced modelling tools were identified as the challenge which is in greatest need of addressing in the near-term, and could be crucial to unlocking cost savings elsewhere in the design lifecycle. Although there are integrated modelling tools which do exist, concept designers have expressed a need for more advanced software to accurately model fully-integrated floating wind systems. Such tools would need to incorporate all aspects of the floating wind system to undertake coupled analysis of the various components. Of particular importance here is the need to incorporate feedback from offshore demonstrations to validate the models. This will also need to be closely tied with efforts to develop advanced control systems. The recently announced DNV-GL joint industry project is a promising development in this area.

Advanced control systems

While most floating platforms claim to be turbine agnostic, it is clear that they will need modifications to their control systems to cope with the different loads and accelerations at the nacelle when supported by a floating structure. Advanced control systems will therefore need to be developed, with close cooperation between OEMs and platform designers. As well as increasing yield and reducing turbulence intensity, advanced control systems can reduce floater motions and support efforts to optimise turbine-platform design and thereby reduce platform size.

Mooring & anchoring systems

The mooring and anchoring system is a critical component which requires further optimisation to reduce both the cost and risk associated with floating wind. While there is a range of mooring and anchoring solutions available which have been imported from other industries, such as oil and gas, these are typically expensive and not necessarily fit-for-purpose for floating offshore wind. This is particularly evident in shallow waters (50-150 metres), where there may be insufficient water depth to develop a proper catenary mooring configuration. Oil and gas platforms are typically deployed in far deeper water, so tailored mooring solutions may be required for floating wind.

Shallow water depths may place greater strain on the anchors, which also need further optimisation. In particular, cost effective anchor solutions will need to be developed for challenging soil conditions (e.g. rock seabeds), which could be particularly relevant to certain coastal regions in Scotland. There may be scope to share learnings or combine R&D efforts in this area with the wave energy sector, which will have similar demands on moorings and anchors.

Related to port-side O&M strategies, a new dimension for mooring and anchoring systems will be the need to develop connections that allow for easy disconnect and reconnect of the platform. This will not have been relevant for other sectors and presents a unique challenge for floating wind.

Advanced tank testing facilities

The gap from part- to full-scale demonstration is a major bottleneck for innovators of floating devices. It may be possible to close this gap through extended tank testing and numerical modelling campaigns, which can de-risk the design and even substitute offshore prototype demonstrations. The current lack of offshore demonstrations and validation with tank testing to date means that this is considered to be medium- to long-term priority for the industry. Over the short-term, the provision of funding to support innovators that need to undertake tank testing campaigns could support early stage concepts that will struggle to develop their designs without an industry partner.

Wind farm operation

The fixed-bottom offshore wind industry has made considerable progress in understanding wake dynamics in an array, with various software tools having been developed that can help to optimise wind farm layouts in order to maximise yield and power output. However, given that a number of floating wind concepts will exhibit a certain amount of lateral motion, the complexity of the interactions between turbines is expected to create additional challenges for floating wind. New tools will need to be developed, or existing tools adapted, that can support developers to estimate and maximise yield, as well as reduce turbulence.

Industry standards

Floating wind has benefitted greatly from the experience of the oil and gas sector. However, a number of concept designers have highlighted that many of the processes and standards inherited from the oil and gas industry may not be fit-for-purpose. Introducing bespoke solutions and new standards for floating wind, building off the guidelines already developed by DNV-GL and ABS, could support the development of optimised and lower cost floating wind designs, as well as encouraging best practice in industry.

Environmental impact

Although environmental impact scored lowly in regards to cost reduction potential, it will have a major impact on the consenting of floating wind farms, and could represent an area of competitive advantage over fixed-bottom offshore wind. However, there is currently a limited body of data to support this hypothesis, and floating wind could learn from fixed-bottom wind in getting ahead of the problem early, to avoid running into some of the consenting hurdles that developers of fixed-bottom projects have encountered. There will be opportunities to leverage work already being conducted regarding bird collisions, but new research will also be required to assess the impact of moorings and anchors on the seabed.

Typology-level priorities

The challenges detailed above are generally relevant for all concepts. However, some of the challenges are more relevant and a more pressing priority for some concepts than others, and this was evident in the variability in technology barrier scoring from designers of different concepts. The top three technical challenges for each of the main typologies are listed in table 5.1.2.

For semi-submersibles, reducing the size of the platform is the main priority for reducing the cost of the system, particularly for steel concepts. However, this will need to still ensure that this does not compromise the stability of the platform and have a detrimental effect on the turbine. As with all concepts, advanced control systems will need to be developed which can support these efforts and ensure high levels of availability. Proving the technical feasibility and cost benefit of port-side major repairs is also essential to the competitiveness for semi-submersibles.

For spar-buoys, mooring design and installation was identified as the most pressing priority. The overall installation procedure is a significant cost driver and priority for spar-buoys, so identifying novel assembly methods which can reduce the need for heavy lift vessels or speed up the installation process could deliver important cost savings for spar concepts. Mating of the turbine to the support structure was highlighted as a particular challenge. As with all concepts, reducing the size of the spar will help to reduce project CAPEX. In particular, for spar-buoys, reducing the operational draft could unlock new markets in shallower water depths.

Anchor design and installation is flagged as the most critical challenge for TLPs, particularly in developing anchor solutions for complex seabed conditions. Installation is also a major challenge for TLPs; namely, improving the installation process such that TLP concepts can be installed quicker and in larger weather windows by reducing the sensitivity to met-ocean conditions. While platform size is less significant than for semi-submersibles and spars, it is still a major cost driver and an areas where TLPs will aim to gain competitive advantage over other concepts.

Table 5.1.2. Key technical challenges by typology

	Semi-submersible	Spar-buoy	TLP
1	> Platform size and weight	> Mooring design & installation	> Anchor design & installation
2	> Advanced control systems	> Platform size and weight (inc. reduced draft)	> Installation procedures (platform and moorings)
3	> Port-side major repair procedures	> Installation procedures (WTG assembly and mating)	> Platform size and weight

5.2 Key Market Barriers

The main market barriers to commercialising floating wind technology are summarised in table 5.2.1. The foremost market barriers identified are related to the perception of floating wind as an expensive and immature technology, which, together with the risk-averse nature of private investors, does not make for a particularly stimulating investment climate. Ultimately, in order for floating technology to advance there needs to be a clear market for floating wind farms, at sufficient scale to justify the necessary levels of investment required from both governments and industry. At present, this market does not exist, largely attributed to the perception that there are plentiful sites for fixed-bottom wind which need to be exhausted before the offshore wind industry looks to deep water solutions.

However, there is a growing evidence base that floating wind has the potential to be cost-competitive with fixed-bottom projects from beyond ~20 GW of offshore wind deployment, by accessing deep water sites relatively close to shore which avoid the need for far-shore offshore wind farms (ETI, 2015). Demonstrating the potential levelised cost of energy (LCOE) for commercial-scale floating wind farms and communicating this message effectively to industry is critical. Although this needs to be complimented by a long-term political commitment that offshore wind will be deployed at sufficient scale over the coming decades, as well as provision of funding to support early pilot projects. Indeed, from a Scottish perspective the most critical market barrier is the lack of clarity for a successor to the enhanced ROCs, which expire in October 2018. Without subsidy support, it is unlikely that any floating wind projects will be built in Scotland beyond 2018.

Demonstrating the cost reduction potential of floating wind will require full-scale demonstrations of the most promising concepts. There is a concern among industry that the current more mature concepts may not be the most cost-effective solutions available. Independent cost benchmarking is therefore needed to assess the various concepts on the market and provide public support to develop those which have the greatest potential to reduce LCOE. The high cost of full-scale demonstrations means that public support is vital to leverage the additional private investment needed, particularly given the increased risk associated with high capital demonstrations of new technologies. Engaging with banks to mitigate the perceived risks and securing insurance from reputable brokers in the offshore wind industry can help to enhance the bankability of the technology and build confidence in the sector.

The perceived technology risk and lack of political certainty over the long-term has made it difficult for concept designers to build partnerships with the industrial backers needed to progress the technology to commercial readiness. This is particularly evident with turbine manufacturers, who have generally been reluctant to diverge from the more mature fixed-bottom market.

As well as the challenge of financing multi-megawatt demonstrations, identifying and gaining consent for suitable test sites has also proved problematic for many designers. In particular, deep water sites close to shore with suitable port and grid infrastructure are not in abundant supply. A handful of sites have been identified in Scotland, but obtaining consent and grid connection approval could threaten the viability of some projects, particularly given the need to commission project before the enhanced ROCs deadline in October 2018. The lack of political certainty beyond this date is creating more uncertainty and risk in the industry, which will only drive up costs further.

Some designers also highlighted the availability of high quality tank testing facilities for floating wind devices, particularly at reasonable costs. Existing tank testing facilities are adequate, but more advanced facilities would support modelling efforts to improve the design of floating wind systems, preparing them for offshore demonstrations.

Table 5.2.1. Key market barriers

Challenge	Mitigation
Perception that fixed-bottom offshore wind sites need to be exhausted before industry moves to deeper floating wind	Demonstrate that LCOE for floating wind in deep water can be lower than fixed-bottom foundations
	Effective communication of the evidence base
Lack of long-term political support	Long-term political commitment, including tariff support for floating wind projects
Lack of awareness in industry of the technology options and LCOE potential of floating wind	Public support for full-scale prototypes of the most promising concepts to demonstrate cost reduction potential.
Identification of the lowest cost concepts – more mature concepts may not be the most cost-effective	Independent cost comparison of the leading floating wind concepts, with demonstrations to validate cost potential
High cost for first prototypes/projects	Funding support from national governments
Financial risk of new technology (bankability)	Multi-megawatt scale offshore demonstrations
	Engagement with banks on pilot and pre-commercial projects
	Securement of insurance from reputable brokers/underwriters in offshore wind industry and maintenance of unscathed track record
Lack of industry partners for innovators – developers and OEMs	Public support to validate the cost competitiveness of floating wind concepts
	Engage with turbine manufacturers through open and continuous dialogue with floating wind community.
Lack of access to high quality simulation facilities at an affordable cost	Investment in test facilities
Availability of offshore test sites	Publically funded test facilities available to industry at reduced cost
Obtaining consent / grid connection	Early engagement with stakeholder and consent authorities to better define differences between floating and fixed structures as well as similarities and advantages

5.3 Recommendations

Addressing the challenges identified in the previous sections presents opportunities for structured innovation programmes to identify solutions and coordinate a strategic approach for floating wind RD&D in the UK. Taking the lead in this area would position Scotland as a hub for floating wind RD&D, creating local economic benefits by leveraging existing capabilities and infrastructure, and potentially unlocking export opportunities to other markets. The recommendations below identify opportunities for future initiatives at four levels:

- **Concept-specific RD&D initiatives** to tackle bespoke challenges and provide funding support for part and full-scale demonstrations
- **Test facility development** to establish the tank and offshore testing facilities needed to demonstrate promising concepts and test innovative component technologies
- **Component-level RD&D initiatives** to tackle common challenges
- **Evidence-base studies** to build a business case for investment in floating wind technology and identify the most effective policy interventions to attract private sector investment

Concept-specific RD&D

Full-scale demonstrations are critical to validating the technical viability and cost reduction potential of floating wind technology, as well as providing a platform for the testing of innovative components that may be common to multiple devices. Concept-specific RD&D will therefore predominantly consist of funding for full-scale prototype demonstrations and pre-commercial arrays. This could involve grants issued directly from funders to innovators through funding calls or a subsidy for the electricity generated from floating wind projects. Regarding the latter, the Scottish Government and DECC should consider a successor to the enhanced ROCs which are set to expire in October 2018. The CfD regime currently offers no uplift for floating wind projects, but a ring-fenced pot for innovative deep water technologies could provide both the funding and competition needed to develop prototype and pre-commercial projects, similar to the approach adopted for wave and tidal technologies.

In the absence of support from CfDs, funding support could be provided through individual capital grants. At present, such funding calls are primarily issued at the European level, with Horizon 2020 and DemoWind both open to submissions to demonstrate innovative deep water technologies. However, the Scottish Government could consider following the lead of government departments in France, Portugal, Japan, and the USA to offer grants to floating wind project developers.

Test facility development

Funding is only one aspect of the challenge to achieve demonstrations, and the lack of appropriate test sites is another key barrier flagged by the industry. Test sites would enable the full-scale testing of individual concepts and innovative component technologies that could have benefits for multiple devices, establishing Scotland as a hub for floating wind RD&D. A designated testing facility could therefore also support earlier stage concepts that are struggling to keep pace with the more mature devices that are progressing to pre-commercial arrays. A test facility with berths for multiple devices would enable testing and benchmarking of more designs to ensure that the most promising gain support for future development.

Offshore demonstrations are vital if floating wind is to come down the cost curve sufficiently to play a major role in the UK's future energy mix. These pilot projects will provide important learnings regarding the manufacture, installation, operation, and overall performance of the design, as well as supporting the component-level activities documented above. To fully capture these benefits in

Scotland, public support is essential to provide the financial leverage and testing facilities to attract projects and investors. Initiatives are already underway to address this (e.g. Highlands & Islands Enterprise developing a test facility at Dounreay), but significant challenges remain and these efforts should be supported to ensure that their development is accelerated in time for demonstration projects to secure the enhanced ROCs available in Scotland up to October 2018.

Component-level RD&D

Given that a number of the challenges identified are applicable to many concepts, there is scope for targeted RD&D programmes to build off the back of full-scale demonstrations and address common challenges that do not infringe on IP sensitivities. These could be assessed at the component level and split by typology where relevant (e.g. different mooring systems for semi-submersibles/spars and TLPs). Possible focus areas for component-level RD&D initiatives are highlighted in table 5.3.1, which ranks the opportunities by cost reduction potential, alongside scoring for the urgency and IP sensitivity of the technology focus areas.

Table 5.3.1. Opportunities for component-level RD&D initiatives

Technology focus area	Detail	Cost reduction	Urgency	IP Sensitivity
Installation optimisation	> Faster installation > Reduce sensitivity to met-ocean conditions > Maximise onshore/port-side operations > Reduce vessel requirements	2.5	2.2	1.8
O&M – major repairs	> Technical viability and cost benefit of port-side versus offshore repairs of major components	2.3	2.2	1.0
Substations / transformer modules	> Develop optimal solutions for transformer platforms (single substation; distributed transformer modules)	2.3	2.0	2.0
Mooring & anchoring systems	> Understanding loads and limitations > Advanced materials for moorings (lightweight, low cost) > Ensure lifetime asset integrity for minimum 25 years > Optimise installation process > Solutions for 50-100m water depths	2.1	2.1	2.0
Wind farm operation (wake effects, yield, power output)	> Understand floater motion and impact on wake effects in floating wind arrays, in regard to both wind farm yield and fatigue > Combine with efforts to develop advanced design modelling tools and advanced control systems	1.9	2.1	1.0
Integrated modelling tools	> Developing advanced modelling software to accurately simulate coupled behaviour of floating wind systems	1.9	2.5	2.0

Technology focus area	Detail	Cost reduction	Urgency	IP Sensitivity
	> Offshore demonstrations and tank testing can be used to validate the accuracy of the modelling tools			
Electrical cables	> Develop and qualify high voltage dynamic cables	1.8	2.1	1.6
Standards and best practice guidance	> Develop a bespoke set of industry standards and guidelines for floating wind devices > Identify opportunities for component standardisation	1.8	2.0	1.0
Environmental impact	> Impact of floating wind structures on the seabed, marine mammals, and local fishing activities	1.4	2.1	1.0

N.B. Scoring from 1-3; High = 3, Med = 2, Low = 1.

Common challenges such as those listed above could be addressed through collaborative RD&D programmes and/or joint industry projects, with government funding leveraging private sector investment. This financial leverage is a key benefit of a collaborative RD&D model, enabling interested parties to pool funds to tackle common challenges and conduct RD&D activities which may otherwise not be possible for individual concept designers or developers. The provision of funding to concept designers and innovators in the supply chain therefore helps to overcome a market failure where high technology development and demonstration costs are prohibitive to the commercialisation of the technology.

An added benefit is the learnings that can be shared between designers and between existing pilot projects. Given the limited amount of funding available for floating wind technology RD&D and the pressing need to demonstrate cost reduction in these pilot projects, collaboration is key to accelerating the commercialisation of the technology. There may also be potential for collaboration with R&D initiatives in other sectors, including oil and gas (e.g. platform design and fabrication, moorings and anchors, installation), wave and tidal energy (e.g. moorings and anchors, dynamic cables, environmental impact), and, of course, fixed-bottom offshore wind (e.g. turbine design, transformer stations, dynamic cables, access systems, wake effect modelling, environmental impact, etc.).

The make-up of such initiatives could consist of either a horizontally integrated programme between floating wind farm developers or concept designers, or a more vertically integrated approach between companies at different levels of the supply chain. This will likely be determined by the nature of the technology challenge and the appetite for collaboration between different stakeholders. In either case, it will be vital to adopt a holistic design approach and engage with component suppliers from across the supply chain, particularly turbine manufacturers, certification bodies, and bank engineers.

RD&D would have greatest impact if based around concept-specific demonstration activities and could be structured around a single test site or multiple sites with wider collaboration between the various demonstration projects set to take place over the next few years (e.g. Scotland, France, Portugal, USA, Japan). Extending the amount of collaboration and cooperation will serve to strengthen the benefits already mentioned above, avoiding the duplication of activity, increasing financial leverage, and maximising the impact of the initiatives.

Evidence-base studies

The impact and legacy of the three opportunities listed above will be dictated by the size of the floating wind market in the UK and overseas. Without a market, the industry will struggle to survive off limited public grants and there is a critical need to engage developers to pull the market forward to full commercial status. Further efforts should therefore be made to build on the work already undertaken by organisations such as the Energy Technologies Institute, The Crown Estate, and The Carbon Trust to highlight the cost reduction potential of floating wind and build a business case for investment in the sector.

Table 5.3.2 highlights a handful of studies which could support the floating wind industry. An early priority is to build on work by Marine Scotland and the ETI to identify the best sites for floating wind in the UK for different types of floating platform, together with LCOE estimates to assess the expected cost competitiveness with fixed-bottom over time. On the back of this analysis, a concept benchmarking study could ensure that the most promising designs are supported and taken forward for demonstration in the respective site locations.

With a number of demonstrations planned over the next few years, there is also an opportunity to assess actual capital expenditure and track the cost reduction achieved from prototype to pre-commercial scale (e.g. Hywind, WindFloat), validating previous cost estimates for the technology. This analysis could be used to develop more accurate estimates for the future cost reduction potential of floating wind at different sites around the UK. Combining this with scenarios for the cost trajectory of fixed-bottom offshore wind will help to identify the level of deployment at which floating wind can be expected to reach cost parity.

It is also acknowledged that the levelised cost of energy (LCOE) is a fairly crude indicator that does not capture the full economic benefits of a given technology. Incorporating LCOE with a broader assessment of the economic, employment, and industrial benefits of floating wind – in line with the 'society's cost of energy' (Siemens, 2014) – will help to better inform investment decisions by the Scottish Government to support an industry which could provide significant domestic benefits and unlock export opportunities for Scottish businesses.

Table 5.3.2. Potential evidence-base studies to support the floating wind industry

Study	Detail
Site identification	> Identify the best sites for floating wind in the UK, including LCOE estimates for comparison with fixed-bottom sites. > Outputs could inform future leasing rounds for offshore wind in the UK.
Concept benchmarking	> Rigorous benchmarking exercise to compare the cost competitiveness of the leading floating wind concepts in different site conditions. > Assessment should include variability by water depth, distance from shore, and infrastructure requirements.
Cost reduction monitoring	> Report on the costs achieved in actual projects to date, including the cost reduction achieved from prototype to pre-commercial scale. > Cost reduction pathway report to identify the future cost reduction potential and scenarios for floating wind.
Socio-economic benefit	> Quantify the potential economic, employment, and industrial benefits floating wind could bring to Scotland, identifying Scottish companies that could enter the floating wind supply chain.

6 Synthesis

Interest in floating offshore wind is gaining momentum, with a number of promising concepts indicating impressive cost projections and several countries looking to exploit wind resources in deep water locations close to shore. Following a handful of early demonstrations, numerous pilot projects are expected to be installed over the next few years, with single prototype and pre-commercial projects planned in Scotland, France, Germany, Portugal, the USA, and Japan, preparing the ground for commercial deployments from 2020. However, a number of market and technical barriers have been identified that will influence the role floating wind could play in the future energy mix of these countries.

Cost estimates from a range of studies suggest that floating wind has the potential to be highly competitive with fixed-bottom wind farms, with the results of this study indicating that LCOE below £100/MWh could be possible in commercial deployments – and as low as ~£85/MWh in leading concepts – with further cost reduction expected over time. In the UK, commercial fixed-bottom projects appear to be on track, or even ahead, of the £100/MWh target by 2020, and costs could fall further as more innovations are brought into projects and cumulative deployments lower the risk and cost of capital for developers. Floating wind must therefore accelerate its trajectory down the cost curve to be able to compete on an equal footing with fixed-bottom projects. Several floating wind concepts claim to be competitive even in shallow water, but given the greater maturity and lower risk of conventional offshore wind technology, fixed-bottom foundations are expected to maintain their dominance over the a of shallow, near-shore sites has been exploited, the baseline cost of fixed-bottom wind farms is expected to increase, as projects are forced to move into deeper waters further from shore. This creates challenges regarding electrical transmission, O&M strategies, and installation, particularly given the increased weather windows required. Floating wind farms could therefore gain competitive advantage by exploiting strong wind resource in near-shore locations at a lower cost of energy than far-shore fixed-bottom projects. The ETI believe that the point of convergence for the UK could be beyond 20 GW installed capacity, with floating wind contributing 8-16 GW if 40 GW of offshore wind is installed in UK waters. Hence, ultimately, there is a need for greater visibility over the scale of offshore wind deployment up to 2050 to allow investment decisions to be made in relation to R&D and infrastructure.

The point of cost convergence is expected to be even sooner in other markets which are more constrained by site conditions and available infrastructure (e.g. lack of installation vessels). The former is also true for Scotland, where deep water and complex seabed conditions create challenges for fixed-bottom projects. If it is able to deliver on its cost reduction projections, floating wind could prove to be an important source of electricity generation in helping Scotland to meet decarbonisation and renewable energy targets at lowest cost. Scotland is particularly well positioned to take a leading role in floating wind technology due to its unique position of being part of the world's largest offshore wind market and its extensive experience and supply chain capabilities from the North Sea oil and gas sector. Floating wind activity would allow Scottish businesses to diversify their portfolios, help to safeguard local jobs, and could create export opportunities to other emerging markets. The existing enhanced ROCs for floating wind are successfully incentivising projects in Scotland up to 2018, but the lack of a successor subsidy mechanism beyond this date is creating uncertainty that could deter investment and drive development to countries with more favourable policies.

With adequate public support, floating wind devices could be ready to compete with conventional fixed-bottom technology by the mid-2020s, provided sufficient deployment and innovation is achieved. But it is clear that costs will need to come down quickly from expensive early prototypes to low cost, optimised solutions in commercial projects. The Carbon Trust conducted a comparative analysis of the majority of leading concepts currently under development to assess the main cost drivers and identified areas where greatest cost reduction can be achieved.

Unsurprisingly, there is a clear correlation between platform weight and cost, with smaller TLP concepts recording lower platform CAPEX than the heavier semi-submersible and spar concepts. The exception to this is in platforms using concrete as the primary material, which, despite a greater mass, is significantly cheaper than steel on a per tonne basis. Lower costs were also seen in semi-submersible and spar concepts which have optimised their designs to reduce platform weight.

Mooring and anchor costs were comparable for semi-submersible and spar concepts, which typically adopt a similar catenary mooring configuration, with the long mooring lines contributing much of the cost compared to the relatively modest anchor costs. Conversely, the shorter and lighter moorings used in TLP concepts resulted in a lower overall mooring cost, though this is compensated by the considerably higher costs of the anchors, which must resist large vertical loads. The net impact was a slightly lower CAPEX for mooring and anchoring systems used in TLP concepts.

Installation was identified as a major cost driver for the different floating wind typologies. In particular, the additional vessel requirements for spar-buoys, namely heavy-lift vessels for erection and turbine assembly, lead to considerably higher installation costs compared to semi-submersibles, which typically only require standard tugs and anchor handling vessels for installation. Installation time and sensitivity to met-ocean conditions also drive up costs, as evident in TLPs, for which the lack of buoyancy stability results in a more complex installation procedure that requires a longer weather window.

The cost of the turbine, balance of system (electrical cables, offshore transformer, development costs), and decommissioning, as well as the yield and annual energy output of the baseline, were kept constant for all concepts to enable a fair comparison of the key metrics, but these are also critical areas which warrant considerable attention. In particular, developing bespoke turbines for floating platforms with advanced control systems and improving numerical modelling tools for an integrated and holistic design approach will support the development of optimised floating solutions with lower platform weight. Developing a better understanding of the wake effects in a floating wind farm and the impact on energy yield will help to optimise array layouts for maximum energy production and reduce structural fatigue from wake turbulence. Meanwhile, RD&D efforts will need to develop solutions to efficiently transmit the electricity back to shore, including producing and qualifying high voltage dynamic export cables and developing low cost solutions for offshore transformers stations (e.g. floating substations, offshore transformer modules).

The cumulative impact of these cost drivers resulted in CAPEX and LCOE figures which were similar for the three main typologies (semi-submersible, spar-buoys, and TLPs), each of which is projecting LCOE values under £100/MWh in commercial deployments. The leading concepts expect to deliver even lower energy costs, at £85-95/MWh, with further reduction possible over time using more industrialised production models. However, there are numerous technical barriers that need to be overcome in order to realise these cost reductions.

Platform size and weight is an obvious challenge and area which could deliver large cost savings. Improvements are already being seen from first prototypes to pre-commercial arrays (e.g. Hywind and WindFloat devices), and additional reductions are expected as designs are optimised further for commercial projects. Installation is another large cost driver and an area which is critical to the competitiveness of floating wind concepts, particularly for TLP and spar designs. Related to this, there is currently not a defined method to conduct port-side repairs of major components, a feature which could deliver considerable OPEX savings and represents an advantage over fixed-bottom wind farms.

To reach cost parity with fixed-bottom offshore wind, improvements will need to be made across the full project lifecycle, and there are additional opportunities for cost reduction across a host of areas, including floating transformer stations, advanced control systems, optimised mooring and anchoring systems, advanced modelling tools, and more. While some of these challenges where there are IP sensitivities will need to be addressed by individual technology developers, there is considerable scope for greater collaboration within industry to tackle common challenges. Furthermore, while certain challenges are more pressing in the near-term (e.g. advanced numerical modelling tools), there are particular challenges which will become increasingly important as deployment scales up to larger farm sizes (e.g. transformer stations, high voltage export cables).

This analysis has informed a set of recommendations on how the Scottish Government can best support the floating wind industry. Given the heterogeneity of the various concepts under development, there is a need for concept-specific R&D to support device development and, principally, to fund pilot demonstration and pre-commercial projects. In particular, there is an urgent need for visibility of a successor support mechanism beyond the October 2018 ROC deadline. This could take the form of a ring-fenced CfD pot or the allocation of capital grants that could leverage funding from the private sector and other European funding sources (e.g. DemoWind; Horizon 2020). Unlocking demonstration opportunities will also require support to develop test sites, as well as the provision of funding for innovators to undertake numerical modelling and tank testing campaigns.

The identification of common challenges with low IP sensitivity presents an opportunity for joint industry projects and collaborative R&D programmes to accelerate technology development and de-risking. Collaboration can foster greater knowledge sharing and attractive financial leverage in order to achieve greatest impact with the limited funding that is available. Government funding can therefore play a crucial role in incentivising private sector participation and generating the market-pull needed to accelerate development and make floating wind a commercial reality. Early R&D projects could involve or take place alongside studies to strengthen the business case for investment in floating wind, including an assessment of the local economic and employment benefits for Scottish businesses, rigorous benchmarking of the most promising concepts for different site conditions, and independent validation of cost estimates.

The RO deadline marks a cross-roads for floating wind in Scotland. Without a successor subsidy support mechanism, floating wind development is likely to stall, with projects concentrating in other less established markets. However, should Scotland decide to continue supporting the industry it has the necessary attributes to position itself as a world-leader in floating wind technology, tapping into the wealth of knowledge and expertise from the already established offshore renewables and oil and gas sectors. Combined with targeted innovation programmes, Scotland could play a central role in commercialising a globally scalable energy source which could help to unlock abundant wind resources in nearshore locations, delivering on government objectives to decarbonise the electricity system and maintain energy security at low cost.

7 Appendix

7.1 Literature Review & Gap Analysis

7.1.1 Literature Review

The Carbon Trust has conducted a review of existing literature on floating wind to understand the current state of the industry and identify gaps that have not been assessed in depth where further research is required. The review has been focussed on industry publications and presentations in the English language, so academic papers, news articles, and literature not published in the English language are not included in the scope of this review. In particular, with regard to the latter it is expected that there is likely to be a significant body of literature in Japanese, given Japan's extensive experience of developing floating technology. In addition, there is a significant number of academic papers which were not captured in this literature review, since this research is considered to be more theoretical and less applicable to commercial application.

During the literature review, Carbon Trust defined a set of 35 different categories grouped in 7 major areas, namely: Geography [5], Market [4], Technology Overview [9], Technology Detail & Components [6], Infrastructure [4], Development & Operation [3], and Commercialisation [3] (no. subcategories in brackets). Using this classification, The Carbon Trust has quantified the relevance of each report assessed on a scale from 1 to 3, considering a weighting of '1' if only general comments or descriptions where provided, '2' for a moderate level of detail and '3' if the reference included detailed assessment of the topic considered. Details on the assessment of each report can be found in table 7.1.1.

Carbon Trust analysis suggests that there is a growing body of literature on floating wind as floating technology begins to gain momentum in the industry with more full scale demonstrations and an acknowledgement that floating wind could play a significant role in the future energy mix of a number of countries with deep coastal basins. There is now more than double the coverage than in 2010, and ten times more coverage than in 2009 (figure 7.1.1). Nevertheless, the literature reviewed has largely been relatively high-level with fairly extensive coverage of the different typologies and various concepts in the market, but few studies which have compared the status, technology readiness, and relative strengths and weaknesses of the competing designs, as well as outlining the steps required to bring down costs and commercialise the devices. There has also been little consideration thus far to the infrastructure and supply chain requirements needed to scale up floating wind in commercial wind farms. A more detailed gap analysis is included in section 7.1.2.

Figure 7.1.1. Floating Wind Publications by Year

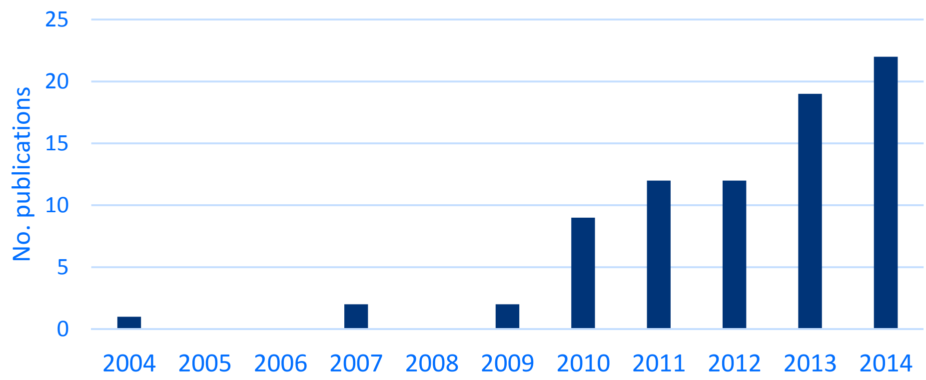


Table 7.1.1. Literature Review Analysis

Scale:
- 1 Basic level of detail
- 2 Moderate level of detail
- 3 Comprehensive detail

				Geography					Market				Technology Overview									Technology						Infrastructure				Development/			Commercialisa		
Author	Title	Year	Type	Global	Europe	UK	Japan	USA	Resource potential	Cost	Policy	Support mechanisms	Typology overview	Spar	Semi-sub	TLP	Multiple concepts	Individual concept	Technology Readiness	Technical challenges	Synergies-other industries	Design modelling tools	Control systems	Electricals/cabling	Anchor/mooring system	Geotechnical conditions	Standards and codes	Supply chain	Port requirements	Fabrication	Installation	Operations&Maintenance	Decommissioning	Environmental impact	Test site	Commercialisation	R&D activities
Watanabe et al.	Very Large Floating Structures: Applicati	2004	Report																		3																
NREL & MIT	Engineering Challenges for Floating Offs	2007	Conference paper										1							2																	
NREL (Jonkman)	Dynamics Modeling and Loads Analysis o	2007	Technical Report																			3															
Garrad Hassan	Floating Support Structures: Enabling Ne	2009	Conference paper		2				2	1			2							2																	
Sway	Powering the future – Marine energy op	2009	Presentation							1				2				2																			
Borgen (Sway)	Floating Wind Power in Deep Water – Co	2010	Magazine article							2				2				2																			
EDP Inovacao	The WindFloat Project	2010	Presentation		2				1						2		1	3										1								1	
GL Garrad Hassan	Floating Offshore Wind Turbines	2010	Presentation										2								2				1		1										
GL Garrad Hassan	Offshore Wind Turbines On TLPs – Asses	2010	Conference paper		2								2			3									2		1			2	2						
Maine University	DeepCwind Consortium - Transforming	2010	Presentation					2					1								2															2	
TU Delft	Floating Vertical Axis Wind Turbines	2010	Presentation												2																						
WindSea	Next generation floating wind farm	2010	Magazine article												2			2																			
Acciona	EOLIA Project and its outcomes in Deep	2011	Presentation														2	2																			
Aux-Navalia	Vessels and platforms for the emerging	2011	Report														2																				
Cahay et al.	Use of a Vertical Wind Turbine in an Off	2011	Conference paper												2		2							2	2		1										
DNV	Design standards for floating wind turbi	2011	Presentation																								3										
DTU	Offshore Floating Vertical Axis Wind Tu	2011	Report												2			3	3																		
NREL (Cordle & Jonk	State of the Art in Floating Wind Turbine	2011	Conference paper																			3															
NREL (Robertson & J	Loads Analysis of Several Offshore Float	2011	Conference paper																			3															
ORECCA	European Offshore Renewable Energy R	2011	Report		3				3											2									2					2		2	1
Riso-DTU	Aero-Hydro-Elastic Simulation Platform	2011	Report											2								3															
Statoil	Hywind – floating wind proven by Statoi	2011	Presentation											2				2																			
DNV	Floating offshore wind power: The next	2012	Presentation				1						2				2																				
EDP Renewables	The WindFloat Project: Deep Offshore W	2012	Presentation		2				1	1					2			3				1						1				1				1	
ETI	ETI's Floating Offshore Wind Demonstra	2012	Presentation																																1		
EWEA	Task Force 'Deep offshore & new founda	2012	Support document		2					2			1				1			1				1					1		1	1					
GL Garrad Hassan	Cost of energy of floating wind	2012	Presentation							2			2							2											2						
James Fisher	Floating wind turbines: The opportunity	2012	Presentation						1				2				2		2		2																
Maine International	Floating Offshore Wind Foundations: Ind	2012	Report	2	2		2	2					2				3																				
Marinet	Collation of off-shore wind-wave dynam	2012	Report																			3															
Norwegian Universit	Design and Design and Analysis of Floati	2012	Presentation										2			2				1																	
Offshore WIND	Floating Wind Turbines	2012	Magazine article	2									2				1																				2
The Crowne Estate (	UK Market Potential and Technology Ass	2012	Report	2	2	3	2	2		2			3						1		2										2	1	1			2	2
Black Rock Wind	Floating Offshore Wind Energy Solution	2013	Presentation												2			2			2																
Blue H Engineering	Offshore Floating Foundations	2013	Presentation							2						2		3		2										1	1	1	1				
Cefas	Floating Wind Turbines: Environmental	2013	Presentation																					1	1									2			
Class NK & KR	FOWT Standardization Research for Offs	2013	Presentation										2				2			2																	
DNV-GL	Design of Floating Wind Turbine Structu	2013	Standard																								3										
DNV-GL	Standards for design of offshore wind fa	2013	Presentation																								3										

DNV-KEMA	Design Standard for Floating Wind Turbi	2013	Poster										2														2										
ETI	Technology and innovation challenges f	2013	Presentation			2			1							2		2																	2		
ETI	Energy Technologies Institute (ETI) FEED	2013	Document															3																			
EWEA	Deep Water	2013	Report		2				2	1	1		2				2			2				1					1		1	1					
Fukushima Offshore	Fukushima FORWARD Project	2013	Pamphlet				3										2							1													
Glosten Associates	Floating TLP Foundation for Offshore Wi	2013	Presentation						1							2		2							2										1		
GustoMSC	Integrated design of floater, mooring ar	2013	Conference paper												2			3		2																	
GWEC	Floating Wind Power: The Next Wave?	2013	Magazine article														2																				
Hall, Matthew (Unive	Mooring Line Modelling and Design Opt	2013	Dissertation										1									2			2												
Maine International	Floating Offshore Wind Foundations: In	2013	Report	2	2		2	2					2				3																				
MERiFIC (Marine Ene	Best practice report - mooring of floatin	2013	Report																						3		3										
Xodus Group	Hywind Scotland Pilot Park Project: EIA S	2013	Project Report			3								3				3						2	2			2	2	2	2	2	2	3	2		
WaveHub	WaveHub Floating Wind Platform	2013	Document																																1		
GustoMSC	Concept design verification of a semi-su	2014	Presentation															3																			
ABS (American Burea	Global Performance Analysis for Floatin	2014	Report										2							2		3		2	2												
Glosten Associates	PelaStar Cost of Energy: A cost study of t	2014	Report							3								3																			
Carbon Trust	Appraisal of the offshore wind industry	2014	Report				3			1			2				2														1						
DEMOWFLOAT	Demonstration of the WindFloat Techno	2014	Presentation																																		
DNV-GL	Floating Wind Technology - Future Deve	2014	Presentation							2										1																1	
DNV-GL	Design standard and third party services	2014	Presentation																								3										
DNV-GL	Control of Floating Wind Turbines: The C	2014	Presentation							1												2	3														
ABS (American Burea	Guide for Building and Classing: Floating	2014	Standard																								3										
FLOATGEN	Windpower going further offshore	2014	Brochure												2		2																		2		
Glosten Associates	PelaStar: 'Four Years Hence' - An Update	2014	Presentation							2						2		3		2											2					1	
IDEOL	Monitoring Floating Offshore Wind Turb	2014	Presentation										1		2			2	1													2		2		2	
International Protec	Intershield Protects: Fukushima FORWA	2014	Magazine article				2																									2					
Marine Scotland	Potential Scottish Test Sites for Deep W	2014	Report			3																													3		
METI Journal	World leading offshore wind. Here.	2014	Magazine article				3											3																			
Nautilus Consortium	Nautilus Floating Solutions	2014	Presentation												2			2																			
Nautilus Consortium	Nautilus: Design considerations for a 5 M	2014	Poster							2								2																			
Nilson & Westin	Floating wind power in Norway: Analysi	2014	Report								2	2	3				2			2				2	2			2							1		
SER (Syndicat des En	Opening new perspectives on marine re	2014	Report		2												2																			2	
Statoil	Offshore Floating Wind: A basis for incre	2014	Presentation																															2			
Statoil	Hywind: A game changing technology	2014	Presentation											2				2																			
Statoil	Hywind Scotland - Developing the UK's f	2014	Presentation											2				2																			
The Crown Estate	Floating Wind: Has Arrived	2014	Presentation						1	1											2																
WindFloat	The WindFloat Atlantic Project	2014	Presentation												2		2	2	1																	2	
Hexicon	Hexicon White Paper	2014	Document															3																			
FORCE Technology	WindSea	Unkno	Brochure												2			2																			
Fraunhofer IWES	HiPRWind: Large floating turbines for in	Unkno	Presentation							1			1							1																	
Fraunhofer IWES	New challenges in wind energy R&D	Unkno	Presentation														2	2																			
InFLOW	InFLOW - The Project	Unkno	Pamphlet												2			2																		2	
Principle Power	Floating Offshore Wind System: The Wi	Unkno	Presentation												2			2																			
RES Offshore	Array cable layout optimisation for float	Unkno	Pamphlet																					2													
University of Bristol	An Integrated Hub Facility for Manufactu	Unkno	Poster			2																							3	2	2	2			2		
Vryhof Anchors BV	Use Of Drag Embedment Anchors For Flo	Unkno	Presentation																						3												
All publications			**89**	**4**	**11**	**6**	**9**	**4**	**9**	**18**	**2**	**1**	**23**	**8**	**15**	**6**	**20**	**30**	**5**	**15**	**7**	**10**	**1**	**9**	**11**	**0**	**10**	**4**	**5**	**4**	**10**	**9**	**3**	**5**	**9**	**11**	**3**
Comprehensive detail				**0**	**1**	**3**	**3**	**0**	**1**	**1**	**0**	**0**	**2**	**1**	**0**	**1**	**2**	**12**	**1**	**0**	**1**	**6**	**1**	**0**	**2**	**0**	**6**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**

7.1.2 Gap Analysis

Subsequent analysis of the literature review work show that some topics, despite being covered in several references, are not assessed thoroughly (e.g. Technical Challenges, Fabrication, Installation, and O&M), while other topics are barely covered at all (e.g. Geotechnical conditions, Policy, Support mechanisms), which is partly attributed to a lack of activity. There is also a general lack of consolidation of information across a number of topic areas (e.g. R&D activities, Test sites). Figure 7.1.2 compares how frequently a topic has been assessed and the number of times these topics have been covered in comprehensive detail. From this assessment the following observations can be deduced:

Geography

Most literature on floating wind emanates from established offshore wind markets in Europe, but there is also material from emerging markets such as Japan[9] and USA. However, few studies present a detailed analysis of the market potential, infrastructure requirements, and best locations for floating wind in a given country. This is also true for the UK, where studies have – at a high-level – identified where water depths and wind speeds are appropriate for floating wind farms, but none have integrated this with the suitability of different concepts and a review of infrastructure requirements.

Market

The majority of publications do not have a geographical focus, particularly those focussing on different floating devices in the market. While some assess the origin of the concepts, no publications assess the relevance and suitability of concepts to particular markets, which will largely be driven by site conditions and available infrastructure. Most country or region-specific studies assess the market potential for floating wind, often based on the level of wind resource in deep waters, but few studies integrate this with an analysis of infrastructure requirements and market factors such as policy drivers and competition with other energy sources.

Studies into the cost of floating wind have also been relatively scarce. GL Garrad Hassan (2012), EWEA (2013) and The Crowne Estate (2013) have produced useful cost estimates, but a lack of operational projects and the range of costs between different concepts makes accurate predictions difficult. There has also been very little work to understand the cost reduction potential and cost reduction pathway for floating wind, as has been conducted for fixed-bottom offshore wind, for example akin to The Crown Estate Cost Reduction Pathways (2012) and LCICG Offshore Wind Technology Innovation Needs Assessment (2011). It is acknowledged that this kind of assessment may be difficult due to the immaturity of the industry, but thorough assessments are considered to be needed to confirm the technology feasibility and encourage investments from the private sector.

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[9] Literature review only covers English language publications. It is expected that there is also a significant volume of literature in the Japanese language.

Technology Overview

A number of publications provide a useful summary of the various floating concepts in the market; however, no reports provide a structured approach to assess the different concepts and make a quantitative comparison between technologies. In particular, there has been little work to compare the technology readiness of the different concepts under development and their suitability to different site conditions and port requirements (e.g. water depth, geotechnical conditions, port draft).

Coverage of individual concepts has again been extensive but high-level, with most material developed for marketing purposes, rather than providing detailed technical insights. The nature of these publications means that they are also susceptible to bias with regard to the benefits of the respective devices. An objective and quantitative comparison of the different concepts on the market, together with their suitability to different site conditions, would be extremely valuable to the industry.

Technology Detail & Components

The technical studies reviewed are generally more academic, rather than targeted to commercial application, and are largely focussed on design modelling tools and control systems for floating structures. However, bar a few examples, they appear to neglect the anchor, mooring, and electrical components of the floating system. Given the challenges experienced in these areas in existing demonstrators (e.g. installation of the 2 MW semi-submersible at Fukushima), greater focus should be applied to integrate the design of the mooring and cabling systems with the floating structure. A concept is only feasible if all the elements that compose it are feasible.

Related to this, there appears to be a large gap around the importance of geotechnical conditions for floating structures. While this is less significant than for fixed-bottom turbines, there are implications for the anchoring systems which are able to be used, as well as understanding the potential cost implications associated with the installation of moorings.

Literature on standards is provided almost exclusively by DNV-GL, who published a standard for floating wind structure in 2013. This is a welcome set of guidelines for designers of floating devices to accompany existing design standards, and more standard development can be expected over time as the technology matures, not only covering design but also manufacturing and installation. However, there could be scope for a study to identify opportunities for the standardisation of certain components in floating devices, including those that are common to either all or specific typologies.

Infrastructure

Literature on floating wind has predominantly focussed on the design of the various concepts under development, but very little attention has been paid to the infrastructure requirements that would be needed to bring these concepts to market. There is a noticeable dearth of material on what would be required to develop a robust supply chain to service the industry, including the sourcing of components, fabrication facilities, and port requirements for installation. This has also not been framed in a geographical context to assess the capability of certain areas to develop a floating offshore wind industry. Opportunities to introduce serial fabrication and optimise installation have also not been investigated.

Development & Operation

As with infrastructure, the operations and maintenance for floating wind farms has received little attention. Given the nascent state of the industry, this is not surprising, but as the first floating arrays approach, this will becoming increasingly important, particularly as the expected reduced costs of major repairs on floating turbines may improve the business case for floating wind. The same can be said for decommissioning, which again is a distant prospect for floating wind farms but is an important consideration when assessing full lifecycle costs for floating projects.

A lower environmental impact is thought to be one of the advantages of floating over fixed-bottom wind farms. While the impact on bird populations is expected to be similar, there has been little work undertaken to assess the impact of floating structures on fish populations and marine mammals. Given the importance of environmental impact in countries looking to develop offshore wind – such as the UK, Japan, and the US – and the synergies that may exist, research in this area could present opportunities to share learnings between geographies.

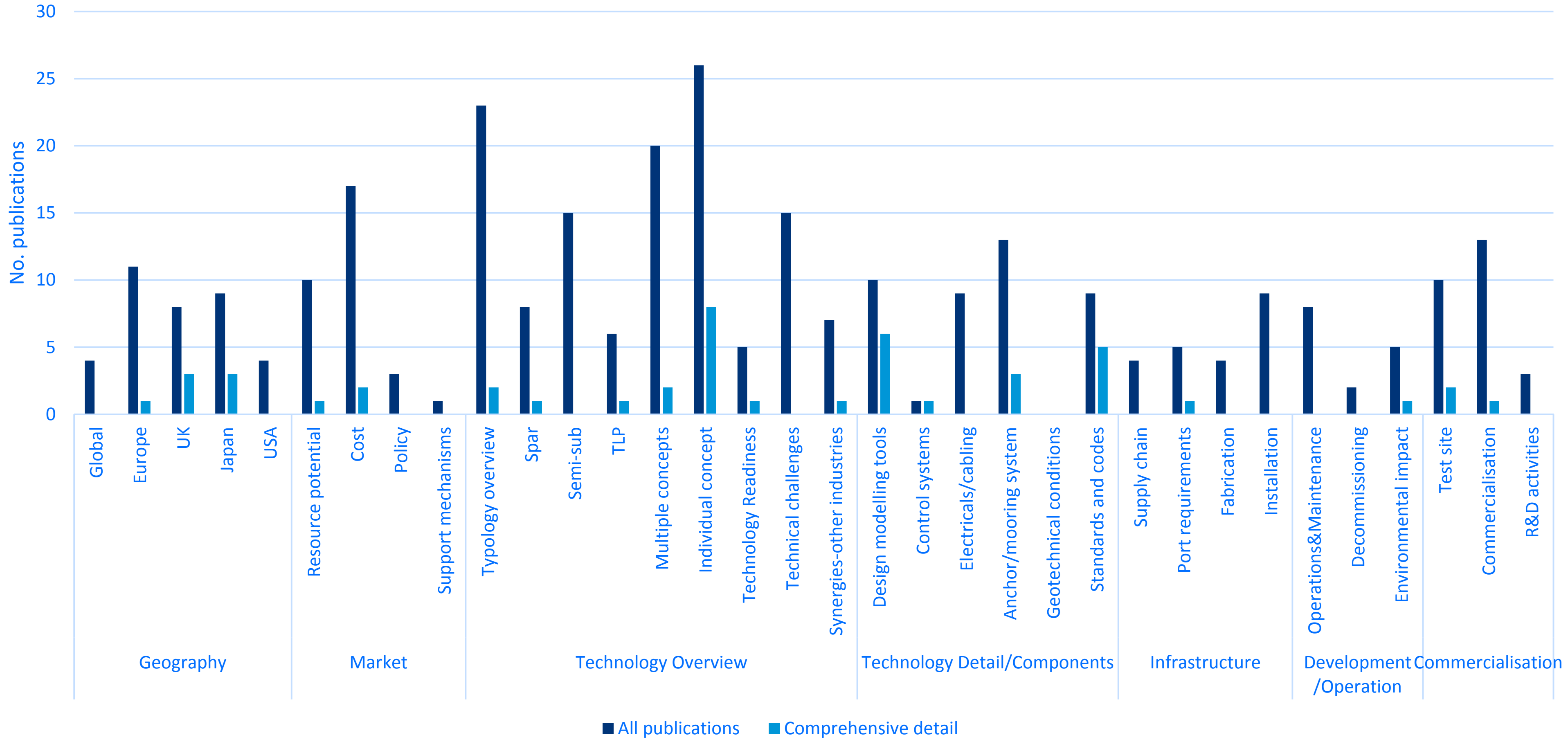
Commercialisation

A number of studies have touched on the commercialisation of floating wind structures, but few have assessed what the pathway to commercialisation could entail. A commercialisation roadmap for floating wind could be a useful tool for innovators and developers to understand what they need to do in order to suitably de-risk their concepts for adoption in commercial projects. A similarly useful follow-on piece of analysis could assess when floating wind can be expected to reach commercialisation and compete with fixed-bottom offshore wind projects, in relation to different policy measures and deployment scenarios.

Critical to commercialising floating wind is the provision of investment for RD&D activities. However, despite a number of research initiatives in this area, there is a lack of consolidation to understand the breadth of RD&D activity in the industry. An exercise to consolidate all historic and ongoing RD&D activities would help to avoid duplication of activity and could inform policy and investment in floating wind RD&D projects. A similar consolidation of the availability of test facilities and offshore test sites for floating wind structures is also absent.

Finally, very few mentions have been found on other socio-economic effects of floating wind farms, such as the impact on the navigation of commercial vessels, the fishing industry, and the oil and gas sector.

Figure 7.1.2. Floating Wind Publications by Topic Area



7.1.3 Concurrent Studies at Time of Writing

The Carbon Trust has engaged with other UK organisations who are concurrently undertaking studies on floating wind in the UK, in order to avoid duplication of activity. Details of the studies can be seen in Table 7.1.2 below. Given that these studies will address some of the knowledge gaps identified in the literature review, such as commercialisation and test sites, The Carbon Trust will address remaining gaps to maximise the additionality of this study.

Table 7.1.2. Concurrent floating wind studies

Funder	Author/Delivery	Study
The Crown Estate	DNV-GL / ORE Catapult	Floating Wind Commercialisation Road Map: Design of a commercialisation pathway for floating wind devices
Highlands & Islands Enterprises	RES Offshore	Assess demand for and required characteristics of a floating wind test site in Scottish waters
Energy Technologies Institute	- BVG Associates - Glosten Associates	- Floating wind cost modelling for UK waters (Glosten PelaStar concept) - FEED study for the Glosten PelaStar concept

7.2 Request for Information (RFI) Baseline

Site location	Water depth	100 m
	Distance from port	50 km

Loads: Aerodynamic (indicative)	Vertical	F_z	7.5 MN
	Horizontal	F_{xy}	2.5 MN
	Moment	M_{xy}	200 MNm
	Torsion	T_z	5 MNm

			H_{max}	T_p
Loads: Hydrodynamic	Return period	50 years	22 m	11.5 - 17.5 s
		5 years	19 m	10.5 - 15.5 s

Turbine:

For comparative purposes, please use the baseline turbine specifications below; however:

- If the concept includes a turbine which is: 2-bladed / vertical axis / other bespoke, please over-write the specifications below, highlighting changes in red font colour. However, please maintain the same power rating.

- If the concept is a floating platform with multiple turbines, please use the baseline conditions below (or bespoke specifications), and answer questions on a per turbine basis (e.g. if the platform holds 5 turbines, divide relevant metrics by 5).

Turbine	Power rating		6 MW [LOCKED FOR CONSISTENCY]
	Axis		Horizontal
	If vertical axis, specify the type of rotor		Savonius / Darrieus / Not applicable
	Number of blades		3
	Hub height (above LAT)		100 m
	Rotor diameter		150 m
	Rotor Nacelle Assembly (RNA) weight		350 t
	Tower bottom	Diameter	6.0 m
		Thickness	30 mm
	Tower top	Diameter	4.5 m
		Thickness	20 mm
	Tower mass		300 t
	Expected capacity factor		40%

7.3 Levelised Cost of Energy (LCOE) Calculation & Assumptions

Calculation:

$$LCOE = \frac{(CAPEX \times WACC) + OPEX}{AEP}$$

Assumptions:

Average wind speed at hub height	Capacity factor	Net annual energy production (AEP) /MW	Weighted average cost of capital (WACC)
9.7 m/s	45.59%	3,910 MWh	10%
10.5 m/s	48.91%	4,284 MWh	10%
11.4 m/s	51.46%	4,531 MWh	10%

Source: Glosten Associates (2014)

8 References

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The Carbon Trust is a world-leading not-for-profit group helping businesses, governments and the public sector to accelerate the move to a low-carbon economy through carbon reduction, energy-saving strategies and commercialising low-carbon technologies. We offer a range of tailored services, designed to meet the needs of businesses, governments and the public sector. By stimulating low-carbon action we contribute to green goals, including the lowering of carbon emissions, the development of low-carbon businesses, increased energy security and job creation.

> We advise businesses, governments and the public sector on their opportunities in a sustainable low-carbon world

> We measure and certify the environmental footprint of organisations, supply chains and products

> We develop and deploy low-carbon technologies and solutions, from energy efficiency to renewable power

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